Renewable and Sustainable Energy Reviews 20 (2013) 443–461

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Progress in solar PV technology: Research and achievement

V.V. Tyagi [a,b,*], Nurul A.A. Rahim [b], N.A. Rahim [b], Jeyraj A./L. Selvaraj [b]

[a] Department of Physics, Manav Rachna College of Engineering, Faridabad 121001, Haryana, India
[b] UM Power Energy Dedicated Advanced Centre (UMPEDAC), Level-4, Wisma R&D, University of Malaya, Kuala Lumpur 59990, Malaysia

ARTICLE INFO

Article history:
Received 3 May 2012
Received in revised form
16 September 2012
Accepted 23 September 2012
Available online 11 January 2013

Keywords:
Solar cells
PV materials
Cost analysis
Environmental impact

ABSTRACT

The development in solar PV technology is growing very fast in recent years due to technological improvement, cost reductions in materials and government support for renewable energy based electricity production. Photovoltaic is playing an important role to utilize solar energy for electricity production worldwide. At present, the PV market is growing rapidly with worldwide around 23.5 GW in 2010 and also growing at an annual rate of 35–40%, which makes photovoltaic as one of the fastest growing industries. The efficiency of solar cell is one of the important parameter in order to establish this technology in the market. Presently, extensive research work is going for efficiency improvement of solar cells for commercial use. The efficiency of monocrystalline silicon solar cell has showed very good improvement year by year. It starts with only 15% in 1950s and then increase to 17% in 1970s and continuously increase up to 28% nowadays. The growth in solar photovoltaic technologies including worldwide status, materials for solar cells, efficiency, factor affecting the performance of PV module, overview on cost analysis of PV and its environmental impact are reviewed in this paper.

Contents

* Corresponding author at: Manav Rachna College of Engineering, Department of Physics, 121001 Faridabad, Haryana, India. Tel.: +91 931 304 5738.
E-mail address: vtyagi16@gmail.com (V.V. Tyagi).

1364-0321/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.rser.2012.09.028

1. Introduction

Due to the fast development, demands of comfort, a higher mobility and growing world population, the energy consumption is rising tremendously year by year. In the present scenario, fossil fuels as coal, oil and gas, are playing lead role to meet the energy demand. The environmental pollution is also serious problem today due to the huge use of fossil fuels. To decrease the pollution and save the environment, renewable energy technologies have good potential to meet the global energy demand. It is known that among renewable energy sources, solar energy is most promising and reliable energy sources in most of the countries, government is providing incentive to setup the solar energy based power plants. In order to convert solar energy in energy forms usable for human needs there are several thermodynamic pathways. In general, heat, kinetic energy, electric energy and chemical energy can be provided via solar energy conversion.

Photovoltaic (PV) is the direct conversion of radiation into electricity. Photovoltaic systems contain cells that convert sunlight into electricity. Inside each cell there are layers of a semi-conducting material. Light falling on the cell creates an electric field across the layers, causing electricity to flow. The intensity of the light determines the amount of electrical power each cell generates. Research on semiconductors (III–V and II–VI) based solar cells were studied since 1960 and at that time, new technology for polycrystalline Si (pc-Si) and thin-film solar cell have been establish in order to lower the material cost and energy input but increase the production capacity [1]. PV is currently a technically and commercially mature technology able to generate and supply short/mid-term electricity using solar energy. However, the current PV installations are still small and provide only 0.1% of world total electricity generation but through some market report indicated that PV installations are growing at 40% average annual rate [2]. PV technology has reduced its unit costs to roughly one third of where it stood 5 years ago, with continuous technical advance and research for efficiency increase, PV will certainly continue on the fast-growing pace and eventually become an important energy supplier in the world. It is predicted by report on the solar photovoltaic electricity empowering the world that PV will deliver about 345 GW around 4% by 2020 and 1081 GW by 2030 [3].

In this paper, the current global status of the PV technology, materials for solar cells such as crystalline materials, thin films solar cells, organic solar cells, hybrid solar cell, dye-sensitized solar cell, nanotechnology based solar cells and environmental impact of solar cells has been reviewed.

2. Worldwide status of solar PV technology

The globally production data for solar cell in 2010 vary between 18 GW and 27 GW. Since 2000, total PV production increased almost by two orders of magnitude, with annual growth rates between 40% and 90% [4]. From 2008 to 2011, PV electricity system prices has been reported decreased by 40% [5]. To this date, it has been reported that world electricity consumption will increase at 2.4% rate per year until 2030 [6]. As the material technology of PV developed, the use of solar power worldwide also increases rapidly year by year. The monocrystalline and silicon materials are covering 80% PV market while thin film materials are chasing rapidly (Fig. 1) [7]. Besides that, new technology like polymer/organic and hybrid solar cell are still in research stages. The PV production from 2000 to 2010 by countries i.e., USA, Japan, Europe and others by JRC European commission report are given in Fig. 2 [5].

It can be seen in Fig. 2 that China is the leader in solar cell production. However, European countries are leading in PV installation with 39 GW power output by the end of 2011 [5]. In European countries, PV installation in Germany, Spain and France are 7.4 GW, 3.9 GW and 1.05 GW, respectively. Meanwhile, developing countries from Asia and Pacific region like India, Malaysia, Taiwan, Korea, Thailand and others also show a good improvement in PV installation since their governments are providing full support in the form of financial incentive for renewable energy project. Indian government is serious for solar electricity production and other renewable energy sources with the setup of a national solar mission to make India as a leader in solar energy and have targeted for 500 GW power production through solar energy by 2030 [8]. Wu et al. [9] conducted research on grid connected PV system in China and concluded that PV technology in China is growing rapidly. From the study it was also found that the China's government provides special fund to R&D group in China for solar PV and also making some policy for PV installation.

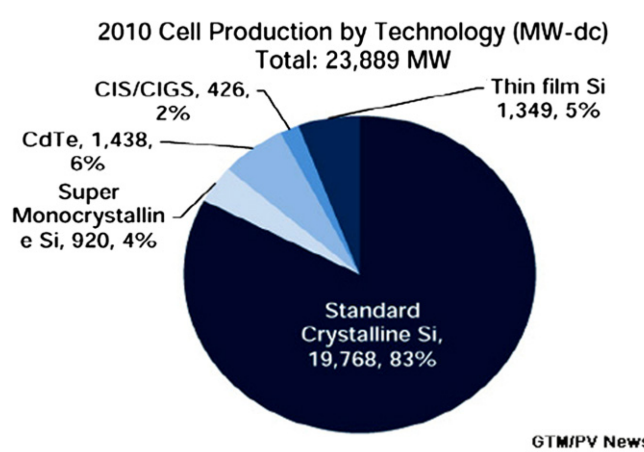

Fig. 1. Solar cell materials market share in 2010 [7].

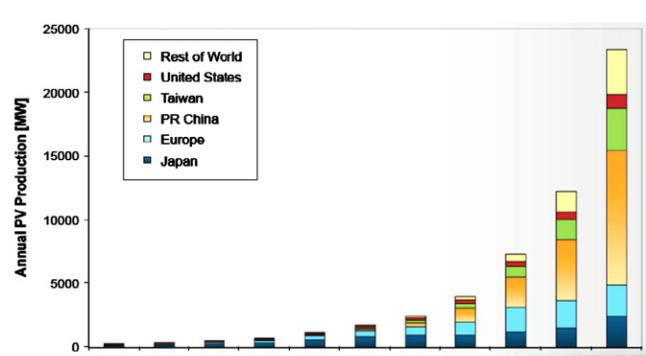

Fig. 2. PV production from 2000 to 2010 [5].

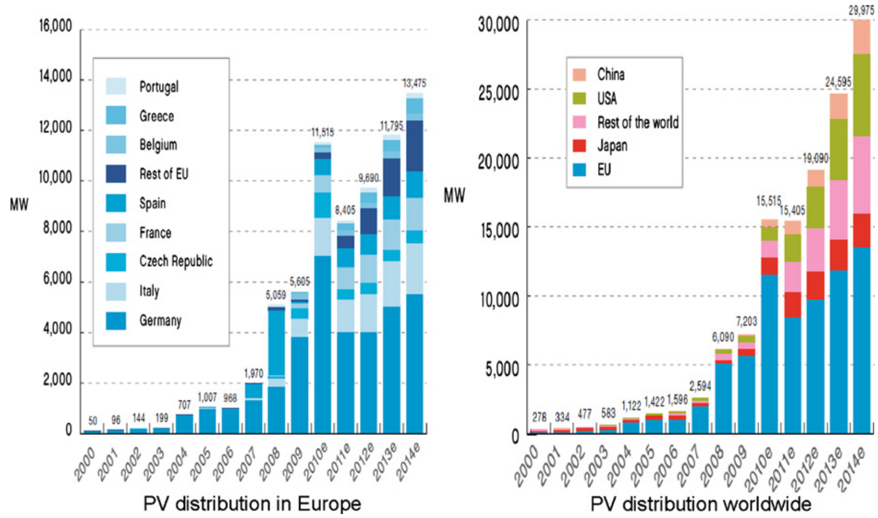

Fig. 3. Comparison of PV distribution in Europe and worldwide [10].

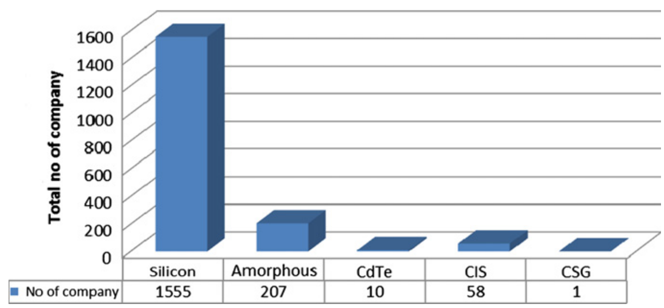

Fig. 4. Materials production companies for solar cell [11].

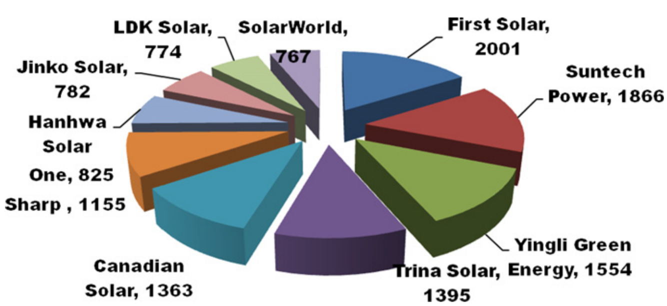

Fig. 5. Top PV cell manufacturer in 2011 by production (MW) [12].

The comparative study of PV distribution in Europe and worldwide are given in Fig. 3 [10]. The predicted result shows that European countries will still lead in PV installation until 2014 while other countries are also growing rapidly in installation. Among European countries, Germany has the highest number of PV installation with 7.4 GW in 2011[10].

Presently, several companies are producing solar cells worldwide and most of them are located in China. Among all the companies, more than 100 companies are producing solar cell based on polycrystalline silicon. On the basis of available data, the different materials production companies for solar cells are given in Fig. 4 [11]. Thin film technology also has a good market share in PV production. Sharp and first solar are among top PV module manufacturers worldwide that are producing thin film technology based solar cell. Fig. 5 shows a worldwide market share of solar cell production companies on the basis of production in 2011 [12].

3. Materials for solar cell

The brief overview on materials for solar cell production is given in Fig. 6. Silicon is a leading technology in making solar cell due to its high efficiency. However, due to its high cost, most researchers are trying to find new technology to reduce the material cost to produce solar cell and to till date, thin film technology can be seen as a suitable substitute [13]. The reasons behind the low cost of thin film technology are because it uses less material and the layers are much thinner compared to mono- and polycrystalline solar cell thus lowering the manufacturing cost. However, the efficiency of this technology based solar cells is still low. Three materials that have been given much attention under thin film technology are amorphous silicon, CdS/CdTe and CIS, but researchers are continuously putting in more effort to enhance the efficiency. However, all of these materials have some bad impact on the environment [14]. Another solution for thin film technology has been carried out by researchers by using polymer or organic as a solar cell material. Polymer materials have many advantages like low cost, lightweight and environmental friendly [15]. The only problem is it has very low efficiency compared to other materials with just 4–5% [14].

3.1. Crystalline materials

From all other solar cell materials, crystalline silicon based solar cell has the highest efficiency compared to others. On top of that, silicon supply can be easily available since it is the second easiest raw material that can be found on earth [16]. The brief overview of crystalline materials is given below.

3.1.1. Monocrystalline cells

This type of material has been widely used in developing PV cells due to its high efficiency compared to polycrystalline cells by 15%. Among other type of solar cell material, monocrystalline solar cell has highest efficiency with more than 20% but for commercialization, the efficiency claim from manufacturer are normally lies between 15% and 17%. Fig. 7 [17] shows the unit cell of silicon whereas most of monocrystalline silicon has been developed using Czochralski process [17]. In this process, high-purity, semiconductor-grade silicon is melted in a crucible, usually made of quartz. Dopant impurity atoms such as boron or phosphorus are added to the molten silicon in precise amounts to dope the silicon, thus changing it into an n-type or p-type silicon.

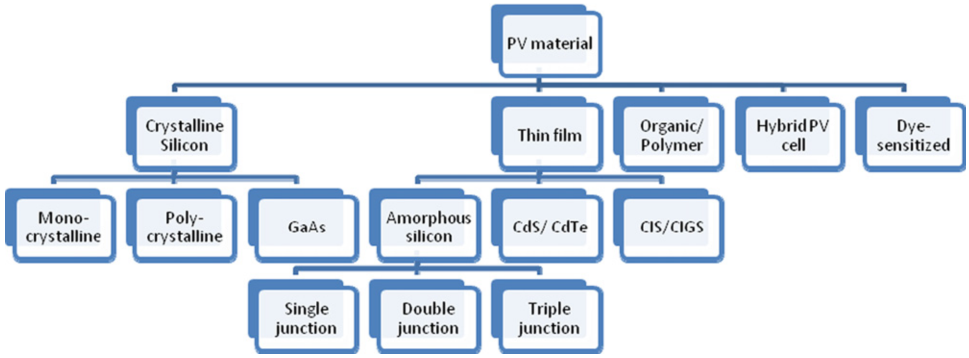

Fig. 6. PV material chart.

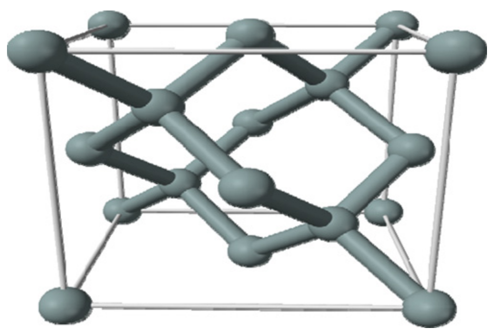

Fig. 7. Unit cell of silicon [17].

This influences the electronic properties of the silicon. A precisely oriented rod-mounted seed crystal is dipped into the molten silicon. The seed crystal's rod is slowly pulled upwards and rotated simultaneously. By precisely controlling the temperature gradients, rate of pulling and speed of rotation, it is possible to extract a large, single-crystal, cylindrical ingot from the melt. Occurrence of unwanted instabilities in the melt can be avoided by investigating and visualizing the temperature and velocity fields during the crystal growth process. This process is normally performed in an inert atmosphere, such as argon, or in an inert chamber, such as quartz [18].

3.1.2. *Polycrystalline cells*

Polycrystalline cell is a suitable material to reduce cost for developing PV module; however, its efficiency is low compared to monocrystalline cells and other developing materials [19]. Even though, polycrystalline cell have low flaws in metal contamination and crystal structure compared to monocrystalline cell [20]. Polycrystalline is produced by melting silicon and solidifying it to orient crystals in a fixed direction producing rectangular ingot of polycrystalline silicon to be sliced into blocks and lastly into thin wafer. However, final step can be abolished by cultivating ribbons of wafer thin ribbons of polycrystalline silicon. Polycrystalline manufacturing technology was developed by Evergreen Solar [21].

3.1.3. *Gallium arsenide (GaAs)*

GaAs is a compound semiconductor form by gallium (Ga) and arsenic (As) that has similar structure as silicon (Fig. 8). Compared to silicon based solar cells, GaAs has high efficiency and thickness is also less. Band gap energy for GaA is 1.43 eV. Efficiency of GaAs solar cell can be increased by alloying it with certain materials such as Al, In, P and Sb. Alloying process will result in formation of

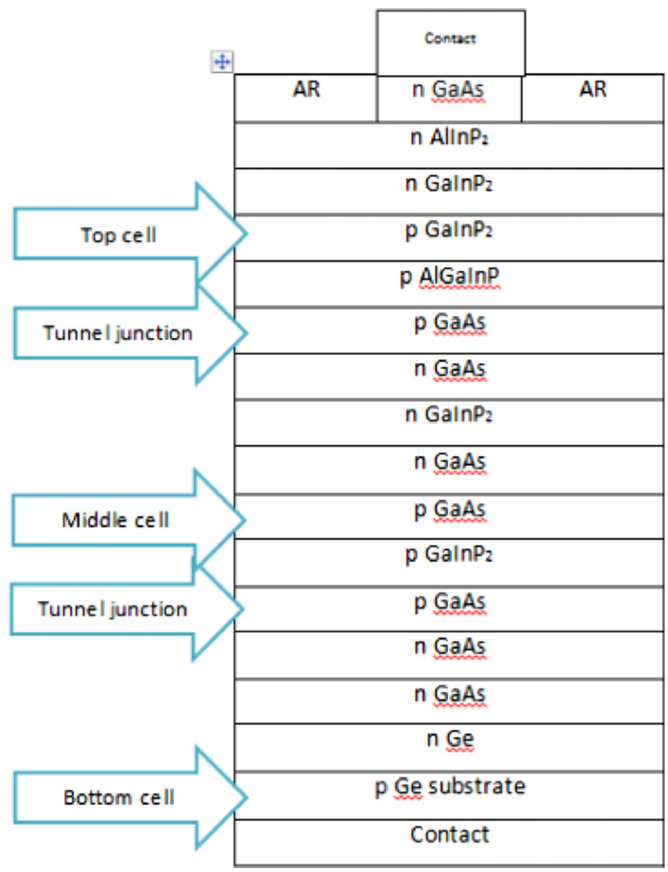

Fig. 8. GaAs solar cell layer [14].

multi-junction devices and band gap values will also be increased [22]. GaAs is normally used for concentrator PV module and for space application since it has high heat resistance [23]. In addition, GaAs is lighter compared to poly- and monocrystalline silicon [24]. However, GaAs material and manufacturing can be costly [23].

3.2. *Thin-film solar cells*

Compared to the solar cells that are based on crystalline silicon, thin film technology are less expensive since it uses few materials and less manufacturing process. Since it uses less material, solar cell that is made from this technology is very thin—around which is 35–260 nm [25].

3.2.1. Amorphous silicon

In thin film technology, amorphous silicon is very popular compared to other material such as CIS/CIGS and CdS/cdTe due to its efficiency [26]. Amorphous silicon is a non-crystalline form of silicon in disordered structure and has 40 times higher rate of light absorptivity compared to monocrystalline silicon [23]. The advantage of its random structure is it gives high band gap which is 1.7 eV [27]. Radue et al. [28] in their paper analyzed the degradation of three technologies of amorphous silicon which are single junction amorphous silicon, triple junction amorphous silicon and flexible triple junction amorphous silicon and found that each materials degrade by 45%, 22% and 27%, respectively.

3.2.2. Cadmium telluride (CdTe) and cadmium sulphide (CdS)

This material can produce high efficiency as 15% and is also known to give an ideal band-gap (1.45 eV) since the direct absorption coefficient is high [29]. The process to produce CdS/CdTe solar cell is by evaporating thin CdS layer on top of a conductive glass substrate, followed by another evaporation of a thick CdTe layer and the deposition of a metal contact layer to complete the initial process. After that, cell will be treated for a short time at a temperature of around 450 °C, usually with a $CdCl_2$ flux that causes a partial crystallization of the semiconductors, and this allows for the copper doping of the CdS in the same process (the flux or other components at the outer interface of the CdTe layer provides the source for this doping) [30]. CdS/cdTe has also been known for their stability for a longer time [31]. However, this technology faces some problem such as environmental related and problem with telluride (Te) raw material [32]. From the experiments that had been conducted from 1950s to 1960s, it was concluded that CdS, when doped with copper, will becomes highly photoconductive since it is an n-type semiconductor [31]. In order to improve CdTe solar cell characteristic, Soliman et al. [33] have conducted an experiment that prove the chemical heat treatment is needed to produce better cells. The cross section view of n-CdS/CdTe heterojunction solar cell are given in Fig. 9.

3.2.3. Copper indium gallium selenide/copper indium selenide

This material is still in its developing phase since it is a new technology and is set to compete with other silicon solar cell. An efficiency of 13% for modules and 20% for cell has been recorded [34]. Its direct band gap can be as high as 1.68 eV with slight modification with Sulphur (S). Radue et al. [28] had conducted an experiment to asses CIGS solar cell performance and lifetime. The experiment had been conducted indoor (under STC) and outdoor for 4 months. It has been observed that the defects on the module will lead to a decrement in current collection. Meyer and van Dyk [35] also conducted an experiment to investigate the performance of CIS and other thin film material. The result from the experiment conducted is CIS only degrades by 10% compared to other thin film material after an outdoor exposure of 130 kW h/m^2. Absorption coefficient of $CuInSe_2$ is greater than 10^5 cm^{-1}.

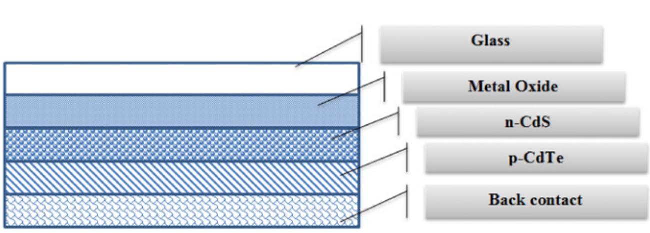

Fig. 9. n-CdS/p-CdTe cross-section [33].

3.3. Organic and polymer cells

An organic solar cell is a new technology and still in its developing phase like CIS/CIGS. Even though it has a very low efficiency which is around 4–5%, but other advantages like mechanical flexibility, disposability and cost efficient has brought much interest in this material [36]. The cross section view of organic solar cell is given in Fig. 10 [37]. Gorter et al. [15] conducted an experiment study to evaluation the performance of 15 polymers for application in PV modules in PV-powered boats. The experiment was focuses on material properties of the polymers such as density, strength, thickness, UV stability, temperature and etc. They concluded that some of the polymers showed the high potential to replace silicon PV modules in the future by considering cost and weight reduction. Most of the organic materials have very low open circuit voltages. The highest open circuit voltage for organic cell was achieved by the Molecular Solar Ltd Company which was 4 V. [38]. Due to that, Peumans et al. [39] suggested that in order to increase the output voltage from organic material, broad absorption band material needs to be found and produced.

3.4. Hybrid solar cell

Generally, the idea of hybrid is by combining crystalline silicon with non-crystalline silicon [40]. Higher ratio of performance to cost has been evaluated by Wu et al. [41] by adopting amorphous silicon with crystalline silicon. One of the biggest solar cell manufacturers from Japan, Sanyo has developed a hybrid solar cell with 21% efficiency. It is called as HIT (combination of Hetero junction and Intrinsic thin film layers solar cell). The base of this solar cell is n-type CZ silicon wafer that functions as a light absorber. Sanyo plans to commercialize this solar cell and plant production is on the way.

3.5. Dye-sensitized solar cell

Due to some problems with efficiency, production cost and environmental related issues of some solar cell materials, researchers have come up with ideas to produce new material technology call dye-sensitized solar cell. The operating principal of dye-sensitized solar cell is given in Fig. 11 [42]. Generally, this type of material has five working principles which are (1) a mechanical support coated with transparent conductive oxides; (2) the semiconductor film, usually TiO_2; (3) a sensitizer adsorbed onto the surface of the semiconductor; (4) an electrolyte containing a redox mediator; (5) a counter electrode capable of regenerating the redox mediator like platine [42]. Dye-sensitized solar cell will be a good competitor to the existing material technology in producing of solar cell [43].

3.6. New technology for PV cell production

Other than searching for new material to improve solar cell output, new technology in processing PV solar cell has been ascertained. Nanotechnology or sometimes referred as "third-

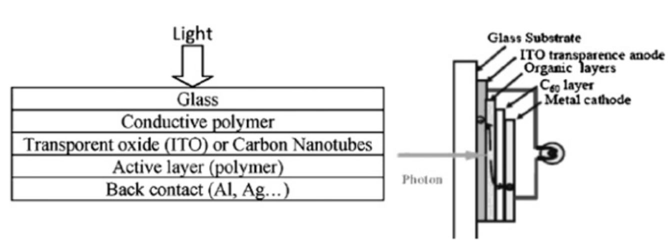

Fig. 10. Organic solar cell [37].

generation PV" [44] is used in order to help increase conversion efficiency of solar cell since energy band-gap can be controlled by nanoscale components [45]. Nanotubes (CNT), quantum dots (QDs) and "hot carrier" (HC) solar cell are three devices used in nanotechnology for PV cell production [46]. The advantages of using this technology are [47]:

(i) Enhance material mechanical characteristic, (ii) Low cost, (iii) Lightweight and (iv) Good electrical performances.

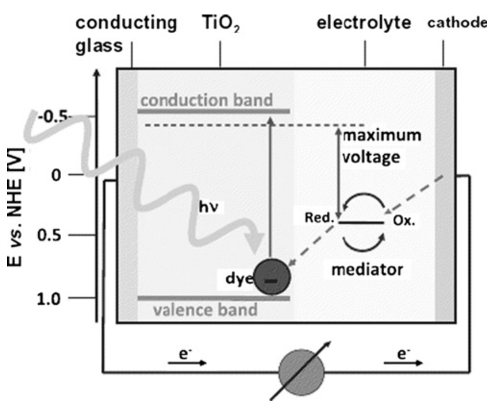

Fig. 11. Operating principle of dye-sensitized solar cell [40].

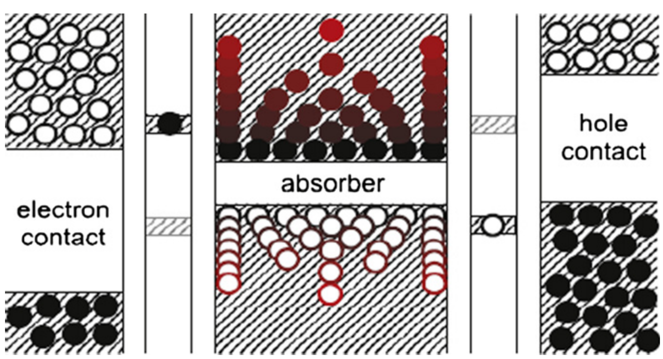

Fig. 12. HC schematic [55].

3.6.1. Carbon nanotubes (CNT)

Carbon nanotubes (CNT) are formed by hexagonal lattice carbon [20]. One research team has invented photodiode solar cell from CNT and successfully improves efficiency and current output from that solar cell [48]. Although the efficiency for solar cell is still low (3–4%), many research will be carried out in this technology to improve the electrical output.

3.6.2. Quantum dots

Quantum dots (QD) can be described as a material that is built with many forms of material thus makes it a special semiconductor system with an ability to control band-gap of energy. Voltage output can be increased as band-gap energy size increases but on the other hand, smaller band-gap can also increase current output. As a solution, QDs are used since they can vary light absorption and emission spectra of light [49]. Aroutiounian et al. [50] developed a mathematical model to calculate photocurrent for the solar cell that is QD based. The model developed is based on two assumptions where (1) QDs are located in subsequent layers, which are periodically stacked M times together at a distance of d (2) $d \gg 0$, where a_0 is typical size of QDs. Efficiency of solar cells based on QD are easily influence by the defects on them [51]. Chen et al. [52] in their experiment had successfully increased the efficiency of quantum dot sensitized solar cell by applying mercaptopropionic acid (MPA)-capped CdSe QDs on TiO_2 film in aqueous solution and concluded that pH value 7.0 is a suitable value to add maximum amount of CdSe QDs on TiO_2 film.

3.6.3. Hot carrier solar cell

Hot carrier (HC) is a challenging method compared to CNT and QD because it needs selective energy contacts to convert light into electrical energy without producing heat. Its efficiency reaches 66% which is three times higher than existing cell made from silicon [53]. But to this date, due to lack of suitable material that can decrease carrier cooling rates, HC has never been commercialized but remain an experimented technology [54]. Fig. 12 shows the schematic of HC solar cell. Konig et al. [55] in their research discussed about principles, material and design of HC solar cell and concluded that materials like BBi, BiN, AlBi, BiP, Bi_2S_3, SiSn, BSb and InP are good as a hot carrier absorber material.

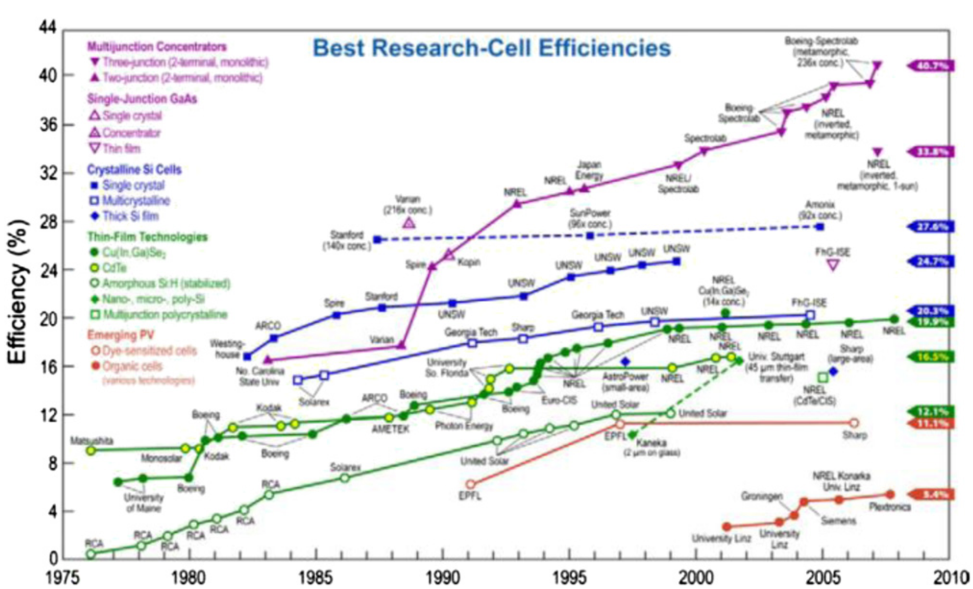

Fig. 13. Solar cell materials efficiency revolution from 1975 to 2010 [1].

4. Efficiency of solar cell

The efficiency of solar cell is one of the important parameter in order to establish this technology in the market. Presently, extensive research work is going for efficiency improvement of solar cells for commercial use. The efficiency of monocrystalline silicon solar cell has showed a very good improvement year by year. It starts with only 15% in 1950s and then increased to 17% in 1970s and continuously to increase up to 28% nowadays. According to Zhao et al. [56] research work, the role of light trapping in polycrystalline solar cell and improvement of contact and surface of solar cell help in increasing the efficiency. The polycrystalline solar cell also achieved 19.8% efficiency to this date but the commercial efficiency of polycrystalline is coming in between 12% and 15% [1]. The different materials' efficiencies for solar cells are given in Fig. 13 from 1975 until 2010. From the figure, it can be seen that GaAs has the highest efficiency among all other solar cell materials with 40.7% efficiency achieved in 2010. The new materials for solar cells i.e., dye-sensitized and organic base cells are still rated at low efficiency with only 5.4% until 2010. The monocrystalline solar cell has 24.7% efficiency, polycrystalline cells with 20.3% and thin film technology with 19.9% in 2010, respectively. The available worldwide PV manufacturer companies with respect of module efficiencies are given in Table 1.

The work of Fraunhofer ISE in the field of high-efficiency silicon solar cells is strongly dedicated to the transfer of high-efficiency cell structures into industrial production [66]. They are working on fabricated laser-fired contacts (LFC) cells on very thin substrates. In order to compare this new technology with a standard laboratory high-efficiency process scheme, laser-fired contacts (LFC) and PERC solar cells have been fabricated on monocrystalline p-type silicon in a resistivity range between 0.5 Ω cm and 10 Ω cm and on n-type silicon with a resistivity of 1 Ω cm in the same solar cell batch. The measured efficiencies for PERC and LFC cells on p-type material with different resistivities are given in Fig. 14. The highest silicon solar cell practical-size (4100 cm^2) conversion efficiency of 22% was achieved by Tsunomura et al. [67]. They developed a cleaning process that achieves a clean c-Si surface and an improved textured structure, a lower-damage-deposition process, a lower-light-absorbing TCO, and a finer grid electrode with reduced spreading area. The progress in conversion efficiency of HIT solar cells with a practical-size of 100 cm^2 in the last fifteen years is given in figure.

Mishima et al. [68] described the development status of high-efficiency heterojunction with intrinsic thin-layer (HIT) solar cells at SANYO Electric. After the year round test for HIT double and single-sided HIT modules (Figs. 15 and 16), the output power of the HIT Double solar cell is higher than that of the single-sided HIT module throughout the year. The HIT double produces 10.9% more output in comparison to a single-sided HIT module. They have also achieved a considerably high open circuit voltage (Voc) of 743 mV, and a high conversion efficiency of 22.8% using only a 98-mm-thick substrate. The result of the study showed that the HIT solar cell has the potential to further improve cost-performance. Chen and Zhu [69] simulated of a-Si/c-Si heterojunction solar cell with high conversion efficiency by the help of computer. They designed a prospective a-Si:H/N^+ c-Si solar cell of high performance with high efficiency of 21.894%, high fill factor of 0.866 and high open voltage of 0.861 V. The simulation results of this study are valuable for further development of high conversion efficiency and low cost solar cells. Friedman [70] described the next-generation high-efficiency multi-junction

Table 1
Worldwide PV manufacture companies with respect of module efficiencies.

Company	Module type	Efficiency	Reference
Suntech power	Monocrystalline	15.30–15.70	[57]
	Polycrystalline	14.50–14.80	
Yingli solar	Monocrystalline	15.30–16.20	[58]
	Polycrystalline	14.10–15.00	
Trina solar	Monocrystalline	14.50–15.20	[59]
	Polycrystalline	13.70–15.00	
Canadian solar	Monocrystalline	13.70–15.26	[60]
	Polycrystalline	12.65–14.12	
Sharp	Polycrystalline	14.40	[61]
	Thin film	10.00	
Hanwha solar one	Polycrystalline	13.60–15.10	[62]
	Monocrystalline	13.30–15.30	
Jinko solar	Polycrystalline	14.05–15.27	[63]
	Monocrystalline	14.36–15.59	
LDK solar	Monocrystalline	14.49–15.67	[64]
	Polycrystalline	13.32–15.67	
Solar world	Polycrystalline	14.31	[65]
	Monocrystalline	14.31	

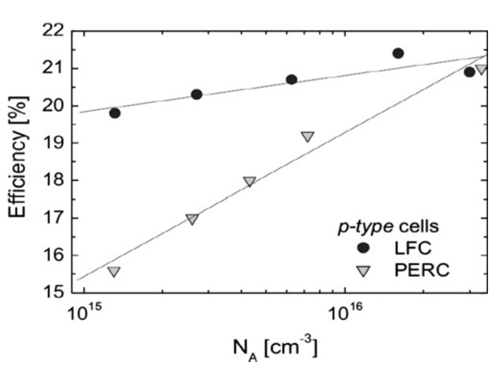

Fig. 14. Measured efficiencies for LFC and PERC cells on p-type silicon [66].

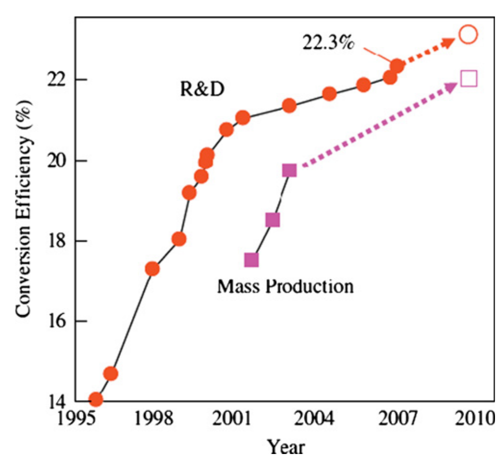

Fig. 15. Progress in the conversion efficiency of HIT solar cells [68].

Table 2
Best demonstrated efficiencies for leading single- and multi-junction solar cell technologies, under one-sun global and concentrated direct illumination [70].

Device	Number of junctions	Efficiency (%)	Suns
Si	1	25.0 ± 0.5	1
GaAs	1	26.4 ± 0.8	1
CIGS	1	19.4 ± 0.6	1
CdTe	1	16.7 ± 0.5	1
GaInP/GaAs/GaInAs	3	35.8 ± 1.5	1
Si	1	27.6 ± 1.0	92
GaAs	1	29.1 ± 1.3	117
GaInP/GaInAs/Ge	3	41.6 ± 2.5	364

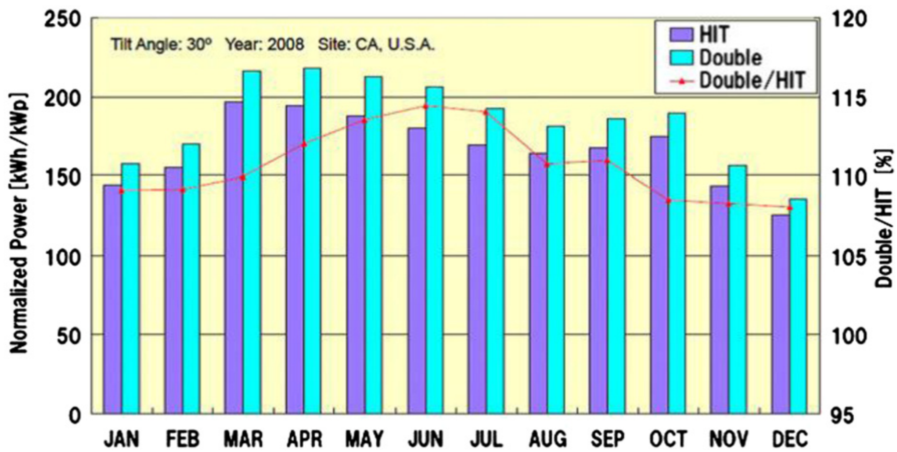

Fig. 16. Output power trends of single-sided HIT and bifacial HIT double modules throughout the year [68].

Table 3
Key issues for realizing super high-efficiency multi-junction solar cells [71].

Key issue	Past	Present	Future
Top cell materials	AlGaAs	InGaP	AlInGaP
Third layer materials	None	Ge	GaInNAs etc
Substrate	GaAs	Ge	Si
Tunnel junction	DH-structure GaAs tunnel J	DH-structure InGaP tunnel J	DH-structure InGaP or GaAs
Lattice matching	GaAs middle cell	InGaAs middle cell	(In)GaAs middle cell
Carrier confinement	InGaP-BSF	AlInP-BSF	Widegap-BSF
Photon confinement	None	None	Bragg reflector etc

solar cells with efficiencies above 40%, is far in excess to the performances of any conventional single-junction cell (Table 2). They concluded that several new generations of multi-junction cells with efficiencies above 40%—are the most efficient cells ever developed. The approaches used to achieve these efficiencies provide paths to continued improvement in cell performance. It is likely that 45% efficiencies will be demonstrated within the next couple of years, while in the longer term, with sustained vigorous development efforts, efficiencies approaching 50% are a realistic goal.

Yamaguch et al. [71] developed high-efficiency multi-junction and concentrator InGaP/InGaAs/Ge 3-junction solar cells with an efficiency of 36.5%. They have also successfully tested a world-record efficiency of InGaP/InGaAs/Ge concentrator three-junction solar cells with an efficiency of 37.4% at 200-suns in 2004. Through this research work, key issues for super high-efficiency MJ solar cells are also given in Table 3. The creation of 40% efficient, multi-junction III–V cells under $500\times$ concentrations is also an important goal for the US photovoltaic (PV) program [72]. The efficiency of cell can be increased by "stacking" multiple layers of semiconductors that absorb different ranges of the solar spectrum. This raises the overall cell efficiency by utilizing more of the solar spectrum per square unit of PV material. Presently, the theoretical efficiencies for four-junction cells using $Ga_{0.5}In_{0.5}P$ are projected at 32%, while GaAs combinations may exceed 40% in certain conditions.

Engelhart [73] reported for a pilot production of multi-crystalline p-type Si cells in the Reiner–Lemoine Research Center at Q-Cells SE with 18% efficiency. The cells were double-side contacted and featured a lowly doped emitter, a fineline-printed Ag grid in combination with plating as front metallization and a dielectric passivized rear with local contacts. They also achieved the median cell efficiencies $>18\%$ over a whole brick and independently conformed top efficiencies of up to 18.35% (UMG) and

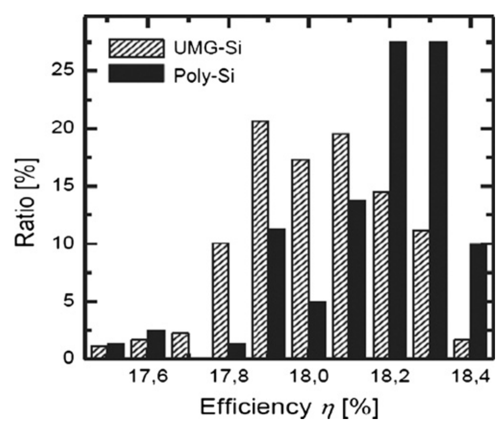

Fig. 17. Efficiency ratio of solar cells from a pilot solar series (300 cells) [73].

18.45% (Poly) on large cell areas (243 cm^2) (Fig. 17). Single crystalline silicon solar cell with energy conversion efficiencies up to 24.7% in a laboratory environment was demonstrated by Zhao [74]. This research provides the variety of silicon substrates, including FZ(B), MCZ(B), CZ (Ga), FZ(Ph) and CZ(Ph) and existing cell efficiency and organizations in Table 4. Gu et al. [75] disclosed about the quasi-single crystalline (QSC) silicon as a potential material to achieve high efficiency for solar cells at a low cost. Compared to multi-crystalline (mc) silicon, the QSC silicon has higher minority carrier lifetime and uniform lifetime distribution. They also suggested that solar cells with industrial standard size, the QSC silicon solar cell is superior to the mc counterpart and can achieve a higher efficiency through an alkaline texturing. The results of this study suggested a great potential for QSC silicon to be applied in photovoltaic industry as the next-generation substrate.

Table 4
High-efficiency silicon cell development and production in other organizations [74].

Cell structure	Organization	Status	Substrate material	Cell area (cm^2)	V_{oc} (mV)	J_{sc} (mA/cm^2)	FF (%)	Efficiency (%)
LFC	Fraunhofer ISE	Suitable for production	FZ	4	679	38.6	81.1	21.3
OECO	ISFH	Suitable for production	FZ	4	666	40.5	78.0	21.1
OECO	ISFH	Suitable for production	FZ	96	649	38.1	81.1	20.0
HIT	Sanyo	In production	n-CZ		~710			21.3
Rear-contact	SunPower	Plan for 25 MW production	PV-FZ	148.8	668.2	38.4	79.6	20.4

Fleischer et al. [76] studied experimentally to enhance the efficiency of thin film solar cell by using transparent conducting oxide (TCO) with absorber and glass. They used three different material layers and compared them for efficiency. The result of this research showed that if $AlZnO_x$ and SnO_2:S, *F* are incorporated with a-Si:H thin film solar cell, efficiency gain will be 6.2% which resulted in total cell efficiency is 9.6%. However, the simulation result showed that total efficiency can be achieved as high as 10.4%. In addition to an increase in efficiency, this technique also decreases the cost per watt of cell.

A reliable pilot-line process for multi-crystalline metal wrap through (MWT) silicon solar cells based on a new contact design was successfully developed by Clement et al. [77]. In this study, few optimization steps were carried out especially the optimization of the via contact, the back side structure and the isolation process. They achieved the cell efficiencies up to 16% and a module efficiency of about 15% by the MWT. The gain was also in efficiency up to 0.6% absolute compared with reference cells (modules) of the same mc Si-block. Morikawa et al. [78] also developed a thin film polycrystalline silicon solar cell with a large area (10 cm × 10 cm). They found that the combination of phosphorus treatment and low carrier concentration BSF were quite effective for thin film Si solar cells to achieve the conversion efficiency as high as 16.0%. Techniques of TiO_2 film fabrication for dye-sensitized solar cells for conversion efficiency of 10% for solar light to electric power were reported by Ito et al. [79]. They used an anti-reflecting film (ARF) to enhance the IPCE or "external quantum efficiency" of the devices to reach up to 94% at wavelengths close to the maximum absorption of the sensitizer and found that the nanocrystalline-TiO_2 layer thickness (12–14 μm) played a crucial role in cell design.

Highly efficient plastic-substrate dye-sensitized solar cells (DSCs) by the press method were developed by Yamaguchi et al. [80]. The conversion efficiency of cell was improved by optimizing the press conditions, the thickness of theTiO_2 layer and the surface treatment of the plastic-substrate. They achieved 8% efficiency of such cells with a 0.25 cm^2 cell area under 100 mW/cm^2. They also fabricated 1.111 cm^2 sized DSC plastic-substrate with 7.6% of efficiency and tested by the national standards institute for photovoltaic measurements in Japan. Yamaguchi et al. [81] also improved the efficiency of dye-sensitized solar cell to more than 10% with the help of Series-connected tandem method. They optimized the dye combination (NKX-2677, N719, NK-6037 and black dye), TiO_2 layer (structure and thickness), and electrolyte (TBP concentration) and successfully obtained an efficiency of 10.4%, which was slightly higher than that of the black-dye single cell.

5. Factors affecting PV cell efficiency

As mentioned in Section 4, it is known that efficiency is a main parameter for establishment of PV technology in the market but some factors are affecting the PV efficiency. The main factors are (1) temperature of solar cell, (2) effect of dust on solar cells, (3) effect of humidity on solar cells.

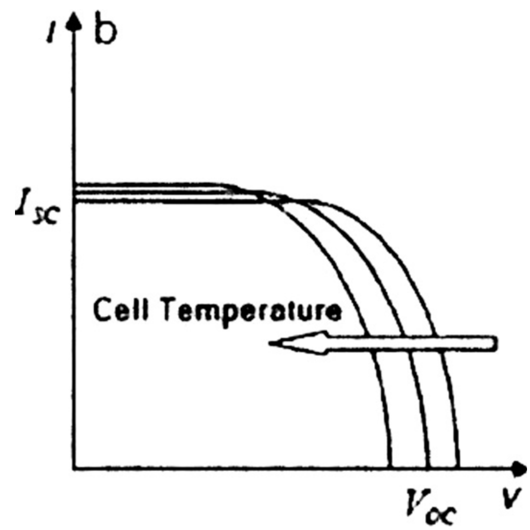

Fig. 18. Effect of temperature on PV cell characteristic [84].

5.1. Temperature

It is widely accepted that efficiency of photovoltaic solar cells decrease with an increase of temperature, and cooling is necessary at high illumination conditions such as concentrated sunlight, or cosmic or tropical conditions. The temperature plays critical factor that leads to a decrement of PV efficiency and its output power. This is due to the shrinkage of band gap as temperature increases, thus the open circuit voltage will drop [82]. During this time, energy charge carriers from valence band to conduction band increase since more incidents light have been absorbed [83]. Fig. 18 shows the effect of temperature on PV cell characteristic [84]. Temperature influence has high impacts on monocrystalline silicon compared to polycrystalline silicon and thin film solar cells. Efficiency decreases by 15% and 5%, respectively for monocrystalline silicon solar cell and thin film solar cell [85]. Singh and Ravindra [86] analyzed a detailed study for temperature dependence of solar cell performance in the temperature range of 273–523 K (Fig. 19). They calculated the efficiency for three cases with temperature i.e., temperature creasing temperature, reverse saturation current increases, and therefore V_{oc} decreases which decreases the fill factor, hence the efficiency of the solar cell as well. At the same time, the band gap also decreases with increasing temperature and this resulted in an increase in J_{sc} which acts to improve the efficiency of the cell. Therefore, the tendency of V_{oc} to decrease and J_{sc} to increase with increasing temperature in the solar cells resulted in a decrease in the efficiency with increasing temperature.

Ting and Chao [87] studied experimentally on temperature influence of photoelectric conversion efficiency with dye-sensitized solar cells (DSSCs). The result of this study showed that the decreasing rates of μ_V, μ_I, μ_P have an increasing trend while temperature rises. From 5.7 °C to 75.5 °C, the maximum value of μ_V was ca. 45%, μ_I

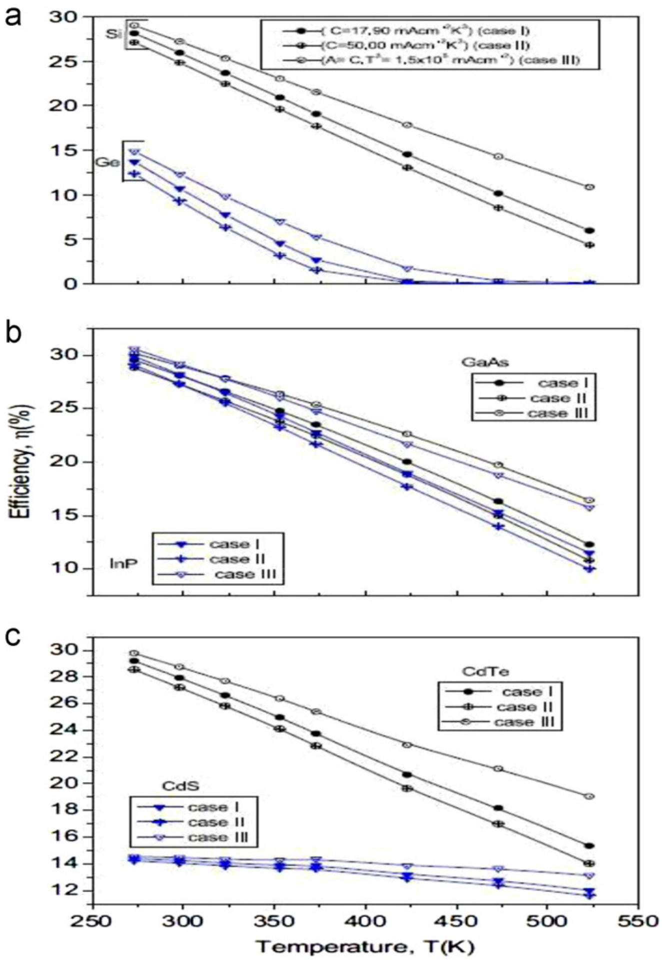

Fig. 19. Temperature effect on PV efficiency [86].

ca. 14%, and μ_P ca. 55%. The decreasing trend in efficiency was also similar with Berginc et al. [88] work for single crystal Si solar cell. Solar cells at a relatively high temperature (around 100–200 °C) and use the excessive heat in a hybrid system to increase the total efficiency of solar cell were studied by Rodriguez et al. [89]. They used high temperature for thermoelectric generator or a heat engine (Stirling engine) to improve the efficiency of solar cells and utilize the heat. They found that the mechanical energy could be converted to electrical energy with an efficiency of more than 90%, which means that the total efficiency of solar-to-electric energy conversion of the hybrid system may be well above 30%, without the employment of expensive materials and technology. Besides, these new cells would be ideal for applications where high temperature is inevitable.

5.2. Dust

Dust is also affecting the PV efficiency because it may block the coming irradiance onto PV modules [90]. Goossens and Kerschaever [91] investigated the effect of wind velocity and airborne dust concentration on the PV cell performance caused by dust accumulation on such cells. They studied experimentally for power output of PV cell at every level. Fig. 20 shows the power output of PV cell for different dust density and different air velocity. From the graph, it can be seen that power output drop drastically as dust density increase.

Jiang et al. [92] tested the effect of airborne dust on three types of PV modules which are (1) monocrystalline (2) polycrystalline and (3) amorphous silicon. The experiments were conducted in a lab, using a solar sun simulator and dust generator. The effects of dust density for every types of PV module are provided in Fig. 21.

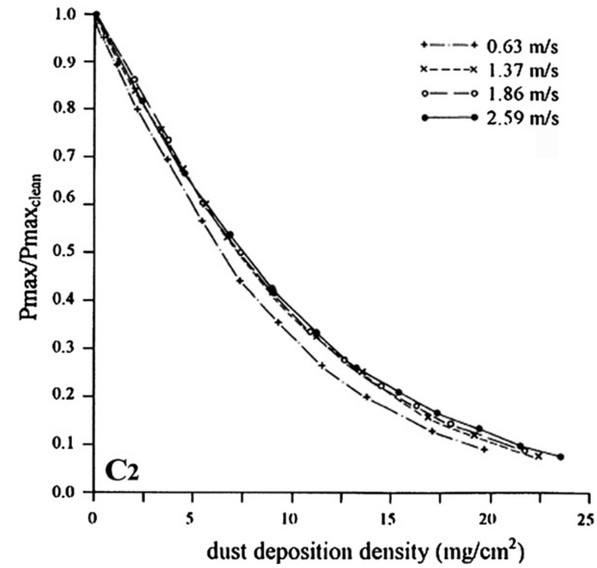

Fig. 20. Effect of dust on PV cell power output [91].

They concluded that airborne dust will reduce the short circuit current and thus affect the efficiency of the PV module and the efficiency drop linearly with the dust deposition density. The results of this study also indicated that dust pollution has a significant impact on PV module output. With dust deposition density increasing from 0 to 22 g/m^2, the corresponding reduction of PV output efficiency grew from 0% to 26%. The reduction of efficiency has a linear relationship with the dust deposition density, and the difference caused by cell types was not obvious.

Elminir et al. [93] studied the effects of dust on the transparent cover of solar collectors. The result of the study showed that the reduction in glass normal transmittance depends strongly on the dust deposition density in conjunction with tilt angle, as well as on the orientation of the surface with respect to the dominant wind direction. Due to the dust deposition density that went from 15.84 g/m^2 to 4.48 g/m^2, the corresponding transmittance diminished by 52.54–12.38%, respectively. A study on the effect of dust accumulation on PV performance was also conducted by Sulaiman et al. [94]. In this study, PV panel was tested with constant irradiation and different types of dust (mud and talcum). The power generated from the PV is shown in Table 5. The result of this study showed that dust reduces the efficiency of PV panel but this effect is decreased as the irradiation level increased. They also suggested for cleaning of PV panel in order to achieve high performance.

Kaldellis and Kapsali [95] simulated the dust effect on the energy performance of photovoltaic generators based on experimental measurements. According to the results of this study, a considerable reduction of PV energy was yielded and efficiency was observed when dust particles were deposited on the panels' front sides and on the mass accumulated on the panel's surface. A similar study for the effect of dust with different physical properties on the performance of photovoltaic cells was done by El-Shobokshy and Hussein [96]. They used different types of dust i.e., limestone, cement and carbon particulates. Well-controlled experiments were conducted using a solar simulator as a light source. For the experiment, five types of dust with different physical properties were used in which three are different classes of limestone, cement and carbon. It is concluded that fine particles gives great effect on the PV performance more than coarse dust. They concluded that fine particles and building material like cement and some others which are present in the atmosphere of urban areas significantly deteriorate the performance of photovoltaic cells through short circuit current and output power when deposited onto the surface of photovoltaic cells.

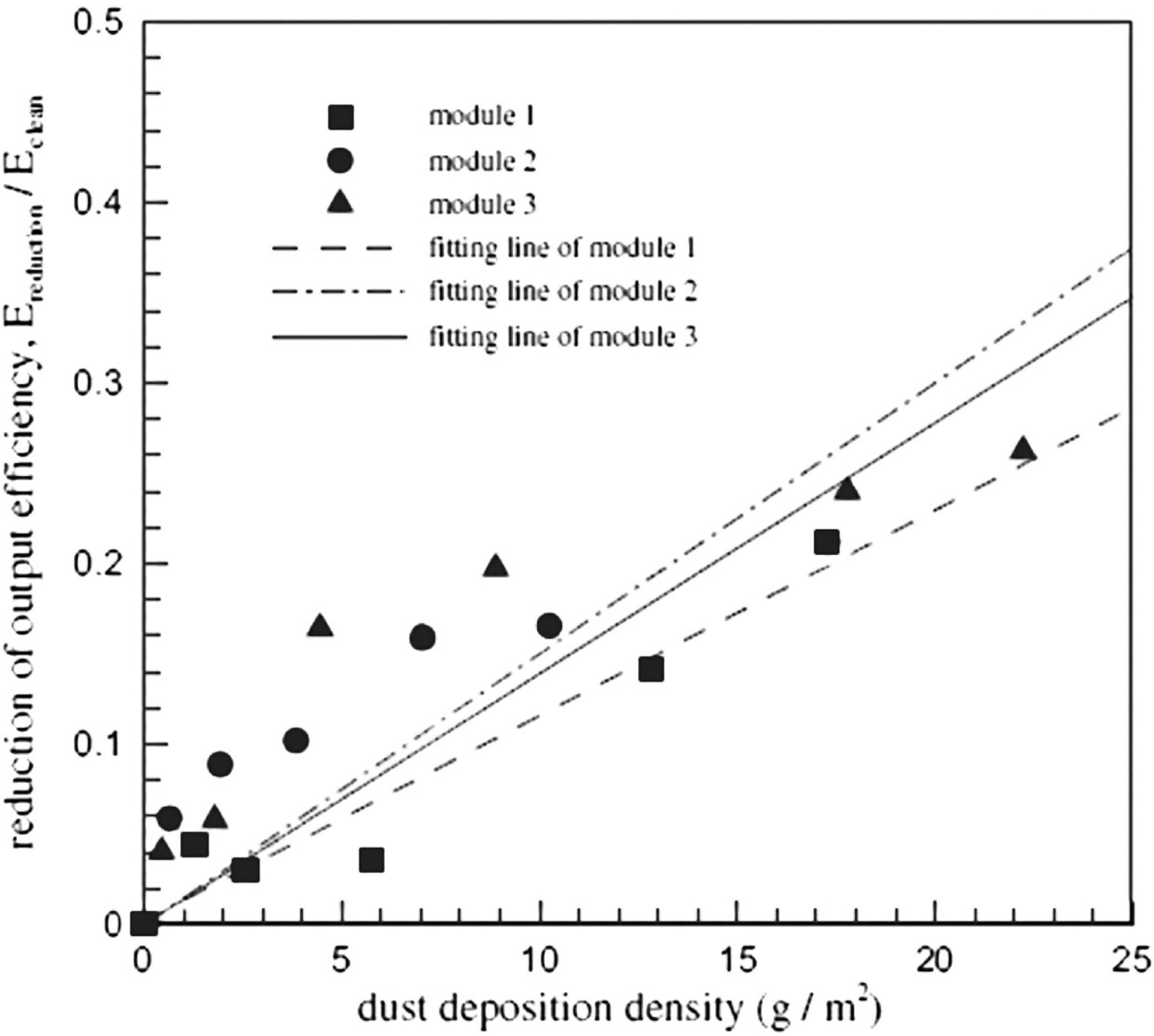

Fig. 21. Dust deposition density effect on PV efficiency [92].

Hee et al. [97] studied for the conditions affecting dust-fall in Singapore and its effect on the optical transmission through glass modules. They found that the transmission through plain glass slides reduced from 90.7% to 87.6%. Samples gathered nearer to sources of dust and other contaminant particles such as heavy traffic, were more adversely affected compared to those which were situated in greenery. They also investigated the effect of substrate tilt in keeping them clean. Bare glass substrates were tilted at angles of 0, 10, 20, 30, 40, 50, 60, 70, 80 and 90 degrees during outdoor exposure. The transmission through the lower parts of the substrates tilted at a fixed angle, was generally worse than the upper part as dust was washed downwards. After 33 days, the average transmission through the upper part of sides was 88.7%, while through the lower part it was 87.9%.

5.3. Solar irradiance

As the solar irradiance increases, the PV module efficiency also increases due to the high number of photons hitting the module. Many electron-hole pairs can be formed if the level of irradiance increase thus will produce more current [85]. Fig. 22 shows the effect of increasing the irradiance on PV cell characteristic [98].

Eikelboom and Jansen [99] conducted an outdoor and indoor test to investigate the performance of nine types of PV modules from different manufacturers. The selected PV modules were Solarex (monocrystalline), Kyocera and Shell (polycrystalline), Siemens (CIS and monocrystalline), United Solar System (Amorphous), ASE (EFG Si Sheet), Free Energy Europe and BP Solarex (Amorphous). After the exposure to outdoor conditions, the CIS module and the amorphous silicon modules showed strong degradation of the maximum STC power. However, monocrystalline modules, as those of Siemens and BP Solarex, did not show any degradation, the multi-crystalline modules of Kyocera and Shell Solar Energy showed very small changes in the IV characteristics and the changes in silicon modules of ASE were negligible. The test performances of all PV modules are given in Fig. 23. They concluded that the performances of thin film technology PV modules were better under low irradiance level condition.

Table 5
Power output from different condition of the PV panel under constant irradiation level [94].

Condition	Peak power (W)		
	225 W/m^2	301 W/m^2	340 W/m^2
No plastic	4.25	4.12	3.62
Clean plastic	4.25	3.75	3.16
Mud	3.48	3.43	3.49
Talcum	3.55	3.22	1.73

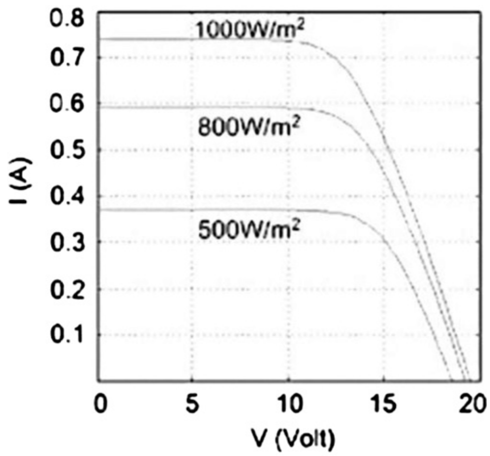

Fig. 22. Effect of irradiance on PV characteristic [98].

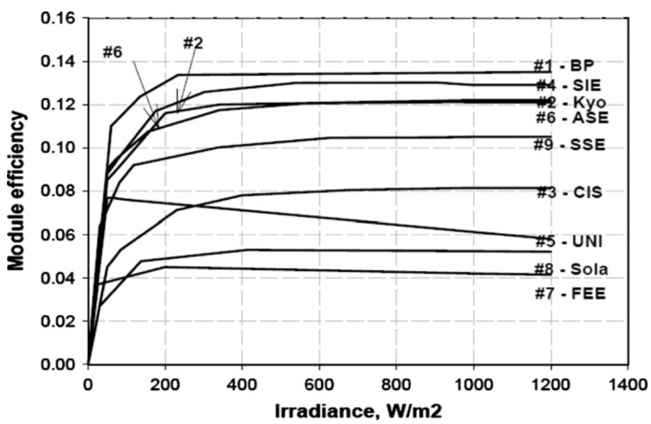

Fig. 23. PV module efficiency by different irradiation level [99].

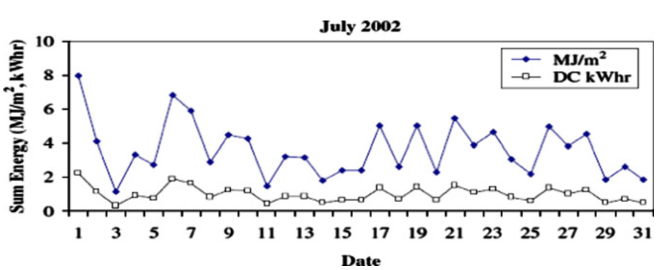

Fig. 24. Energy output of PV for low radiation under 400 W/m^2 [101].

A solar radiation database for PV performance in Europe and Africa was studied by Huld et al. [100]. The study was based on database from 20 stations with the help of PVGIS. The validation results of this study showed that the overall mean bias errors of PVGIS-CMSAF was low, at about +2.0%, while the standard deviation of individual station MBE values was 5.0%. This data is also useful for the detailed calculation of off-grid systems than the one presently possible with daily irradiation data, and to check the accuracy of the algorithm used in the off-grid web application of PVGIS. Thongpron and Kirtikara [101] study focused on the effects of low radiation on the power quality of a distributed PV-grid connected system. They investigated for a 4.2 kW/p array of roof top units and observed that a PV array generated increasing amount of real power, in magnitude and as percentage of complex power, at high values of radiation. At low radiation level, when the array does not provide enough output power, reactive power was drawn from distribution transformer and fed into an inverter and loads. Based on results from the test site and long-term radiation data of Bangkok, they estimated that for a tropical climate like Thailand, a significant amount of radiation energy, around 20–30% is available in the form of reactive power (Fig. 24).

The variations of the solar spectrum of relevance to thin film solar cells were studied experimentally by Gottschalg et al. [102]. The study was based on three thin film cells i.e., CIGS, a-Si and CdTe. On the annual basis, the most affected thin film material was a-Si. It was estimated that the useful fraction for a-Si varies from +6% to −9% with respect to the annual average. CdTe and CIGS vary in the range of +4% to −6% and ±1.5%, respectively, around the annual average. Yoo [103] also investigated the power output of BIPV for one year by simulation and field experiment method in Korea. The relationship between power output and irradiation level has been plotted in Fig. 25. They observed that during afternoon when the irradiation level was normally maximum, the power output generated by the PV modules was also maximum. The result of this study concluded that PV performance depends on solar irradiation level that hits on its surface. The simulation result also shows good agreement with the experimental result.

6. Cost analysis for PV

In this section, cost analysis of solar cell is given on the basis of available research papers and companies literature. It can be seen that in the past decades, the cost of different materials for solar cells are decreasing through the effort of research and development in the field of material science. By comparison to the other solar cell materials, it was found that monocrystalline silicon has good efficiency for the use of solar cells but the manufacturing process is complex, thus the increase in production cost. [104].

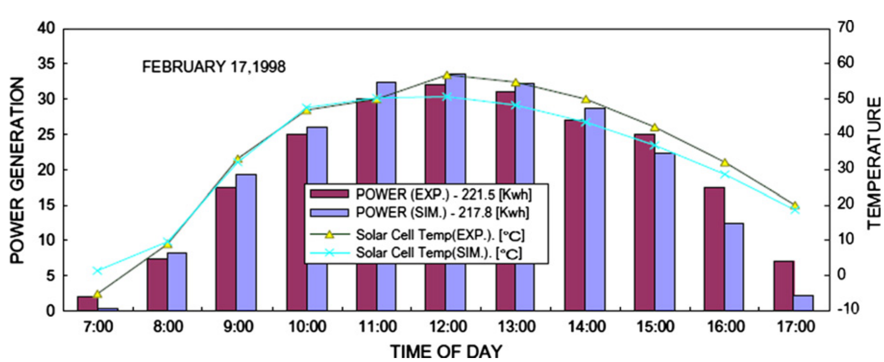

Fig. 25. PV power generation related to irradiance in a day [103].

Table 6
Manufacturing cost of terrestrial modules [105].

Option	1996 (price)	2000 (cost/price)	2010 (cost/price)
Single XTAL	3.30–4.25	1.50/2.50	1.20/2.00
Polycrystal	3.20–4.25	1.50/2.50	1.20/2.00
Ribbon	–	1.50/2.50	1.20/2.00
Concentrator (module plus tracker motor/electronics)	4.00	1.20/2.00	0.80/1.33
Amorphous 81 (double stacked)	3.00–3.50	1.20/2.00	0.75/1.25
T1 spherical	–	1.20/2.00	1.00/1.67
CIS	–	1.20/2.00	0.75/1.25
SI Film on LCS	–	1.20/2.00	0.75/1.25
Low price (BAU)	3.75	2.50	2.00
Low price (ACCEL)	3.00	2.00	1.25

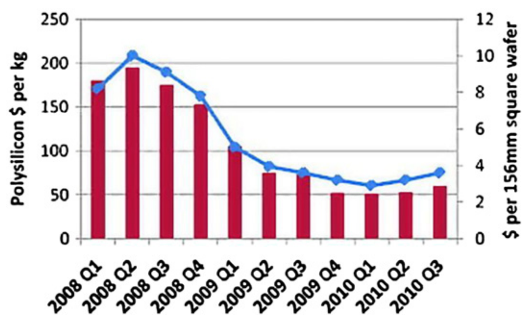

Fig. 26. Poly-silicon price from 2008 to 2010 [107].

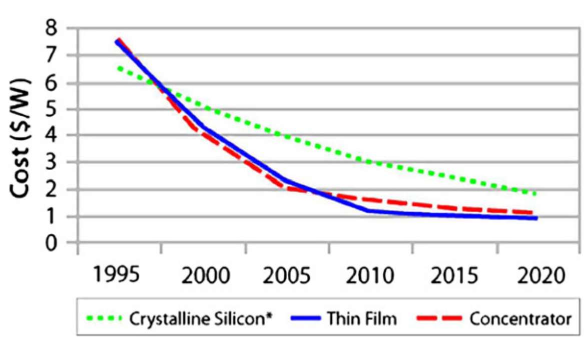

Fig. 27. Cost of PV panel from 1995 to 2020 [110].

The cost for per watt of monocrystalline material was nearly \$3.97 in 1996 [23]. The polycrystalline silicon solar cell material is less expensive compared to monocrystalline solar cell and the manufacturing process is also simpler [105]. The cost analysis for poly and monocrystal PV module from 1996 to 2010 are predicted by Maycock [105] (Table 6). From the table, it can be seen that the prices for each materials decrease year by year which is possible by the help of [106]: (i) innovation in material technology, (ii) increase in the amount of PV module production, (iii) improvement in efficiency by the help of new technology (iv) lifespan of PV systems, (v) policy in favor of renewable energy.

The cost of poly-silicon material based on each quarter from 2008 to 2010 is given in Fig. 26. The highest price can be seen during 2008 due to a high demand but limited source but the cost decreases in each quarter [107]. The thin film technology has also poses a challenge to crystalline silicon forcing it to become cheaper. Another thin film technology called CdTe/CdS which suffer from problems like availability of raw materials and environmental issue, however, stands at a low cost which is at \$2 per peak watt [108]. For the module installation on the rooftop

Table 7
Cost analysis calculations for PV module based on silicon [111].

Item	2012	2020
Module efficiency (%)	14.5	20.5
Cell thickness (μm)	180.0	50.0
Material utilization (%)	0.45	0.90
Contract Si price (\$/kg)	40.0	25.0
Base labor cost (\$/h)	15.8	18.5
Labor content (ppl/MW/a)	2.9	1.5
Electricity cost (\$/kW h)	0.07	0.09
Capital cost (MM/MW/a)	1.08	1.19

Table 8
PV panel price by company and power comparison.

Company	Technology	Power (W)	Price (€)	References
Avancis	CIS	110	196	[112]
Q Cell	CIS	95	174	[112]
Kyocera	Polycrystalline	135	247	[112]
Solarpark	Polycrystalline	240	374.9	[112]
Solar world	Polycrystalline	225	288.68	[113]
LG	Monocrystalline	250	382.9	[112]
Sanyo	Heterojunction with intrinsic thin layer	214	418.9	[112]
Schott solar	Monocrystalline	190	308	[112]
UNI-solar	Amorphous	124	179	[113]

of domestic purposes, customers need to add approximately \$5 more per watt depending on the size and location of installation. Federal tax for PV module installation also depends on every country which can bring up to 50% from the cost of installation [109]. The PV panel cost by material from 1995 to 2012 with prediction for price up until 2020 was analyzed by Adams et al. [110]. It can be seen that PV price dropped drastically since 1995 to 2012 and the cost is near to \$3 per watt (Fig. 27). It is predicted that in eight years from now, the cost will be only around \$1 per watt for thin film technology and \$2 per watt for crystalline type [110]. The cost analysis calculations for silicon based PV module are given by Powell et al. [111]. This analysis included the material cost, labor cost, electricity cost and capital cost to produce PV module for 2012 and also predicted the polarity of the cost in 2020 (Table 7). They predicted that in 2020, base labor cost, electricity cost and capital cost will increase due to economic development. On the basis of available data, the PV panel prices for different companies with power comparison are given in Table 8. The efficiency of PV material and their manufacturing cost per watt with market share are also given in Fig. 28 [114].

The thin film solar cell has lower cost compared to silicon but still lacks in efficiency while organic cell and third-generation of PV are still under research. Polymer solar cells have been a very good competitor in production cost compared to crystalline solar cell. Not only is it cheaper, it can also be produced at a fast rate [115]. An overview of polymer materials for PV is given in Table 9. Kalowekamo and Baker [116] has estimated the cost to produce an organic solar cell by considering material cost, processes cost including capital and labor and also overhead cost. As a result, they found that manufacturing cost for organic solar cell lies in range of \$48.8–\$138.9/m^2. Thus the module cost is around \$1.0–\$2.83/Wp for module with 5% efficiency. Nielsen et al. [117] analyzed on business, market and intellectual property for polymer solar cells and presented the actual cost which includes material and processing cost to develop one solar cell with 360 cm^2 and 660 mW power output as €5.3491. Emmot et al. [118] stated that for 0.27% efficiency of organic solar cell, the EPBT will be 5 years while the cost range is 16.09 €/Wp and

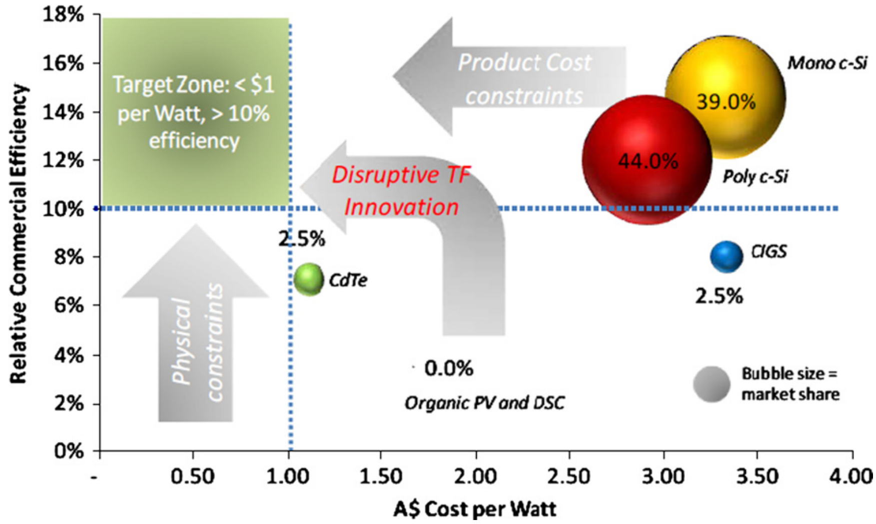

Fig. 28. Commercial PV efficiency vs. cost per watt [114].

Table 9
Polymer material for PV [15].

Material type	Cost per kilogram (€/kg)	Material type	Cost per kilogram (€/kg)
Epoxy	1.96–2.15	FEP	16.30–24.70
Epoxy with glass fiber (15–50%)	3.68–4.05	FEP with glass fiber (20%)	18.40–20.20
ETFE	20.00–30.00	PEI	10.80–11.90
ETFE with glass fiber (25%)	20.70–22.80	PEI with glass fiber (30%)	8.86–9.74
PI	29.00–35.00	PTFE	8.00–16.00
PI with glass fiber (30%)	23.50–25.90	PTFE with glass fiber (15% and 25%)	10.90–13.10
PE	1.10–3.54	PMP	7.47–9.13
PE with glass fiber (20–30%)	2.18–2.61	PMP with glass fiber (10–30%)	7.43-8.17
PP	1.12–2.37	TPU	8.67–9.54
PP with glass fiber (10–50%)	1.90–2.92	TPU with glass fiber (40%)	4.30–4.73
PVDF	12.30–18.50	EVA	0.49–0.55
Silicones	9.88–10.90	PB	1.55–1.70
PEN	2.67–2.94	Glass	1.25–1.39

33.33 €/Wp. However, there are no companies that produce organic solar cell as of yet since this technology are still in research stage.

Branker et al. [119] reviewed about the solar PV electricity cost. They estimated the recent cost of system installation worldwide (Table 10). It should be noted that the average installation costs for residential systems are lower in Germany and Japan than in the United States. A 2 GW solar power plant based on CdS/CdTe was installed in Waldpolenz, Germany and in this power plant, 40 MW PV module is setup by First Solar at the cost of €3250 per kW and another 7.5 MW system was installed in Blythe, CA, where the California Public Utility Commission has agreed to a power delivery price of 12 cent per kW h [31]. Oerlikon Solar from Switzerland however claimed that they have a technology that can cut the manufacturing cost of thin film solar cell to €0.50 per peak watt [120]. This is the first company that set up a 1 GW scale solar cell factory that is based on CIS technology [120]. To this date, there are many researchers that are studying on techniques to lower the processing cost of thin film by sophisticated vacuum co-evaporation [121], sputter deposition of a metal-alloy [122], stacked elemental layers process [123] and many more.

7. Environmental impact of solar PV technology

In order to generate electricity by PV module, some manufacturing processes are needed to produce PV module with different materials. The life cycle of PV module is given in Fig. 29 [124]. The environmental sensitivity factors and key points of pollution prevention, environment impact analysis and life cycle assessment for crystalline PV system (Fig. 30) were discussed by Zhang et al. [125]. The discussion was about the most serious environmental problems in PV industry of polysilicon cell. Polysilicon cell manufacture chain contains "High-purity multi-crystalline Si", "Si wafer", "Mono- and multi-crystalline Si cell", "PV modules seal". In the process of high-purity multi-crystalline Si production, metallurgical silicon is transformed into $SiHCl_3$, and then $SiHCl_3$ is deoxidated by hydrogen. In the whole process, about 25% of $SiHCl_3$ is turned into polysilicon, and the rest is poured into the exhaust gas, generating the by-product-SiCl4. The solution suggested is for PV system to be decommissioned at the end of its useful life, recycled and disposed of safely to keep the environmental harm to a minimum, alleviate the raw materials shortage of PV devices to some extent, and avoid waste of resources. The environmental impact assessment for this stage should focus on different recycle technical methods for PV systems.

As discussed above in material technology part, different materials i.e., silicon, CIS, CdTe and others are used in solar cell manufacturing. In order to get the raw materials for PV production, mining operation needs to be done and this may cause danger to miners. In addition, mining machine involves usage of petrol and diesel so it may cause air pollution [124]. The emission of hazardous gases and heavy metals from different types of PV materials are given in Figs. 31 and 32. It can be seen that dye-sensitized PV

Table 10
Summary of recent solar PV installed system costs [119].

Solar PV technology	Installed cost [\$/W_p]	Project scale
Crystalline (Europe)	5.00	Utility
Crystalline (China)	4.42	Utility
Crystalline (Japan)	5.02	Utility
Thin-film CdS/CdTe	4.28	Utility
Thin-film a-Si/μ-Si	3.52	Utility
Crystalline and thin film (USA)	7.50	Capacity weighted average (2009)
Crystalline and thin film (Germany)	7.70	Residential (2–5 kW) (2009)
Crystalline and thin film (Japan)	4.70	Residential (2–5 kW) (2009)
Crystalline and thin film (USA)	5.90	Residential (2–5 kW) (2009)
Crystalline and thin film (CA,USA)	7.30	Residential $\leq$(2–5 kW) (2009)
Crystalline and thin film (CA,USA)	6.10	$>$100 kW (2010)

Fig. 29. Life cycle of PV module [124].

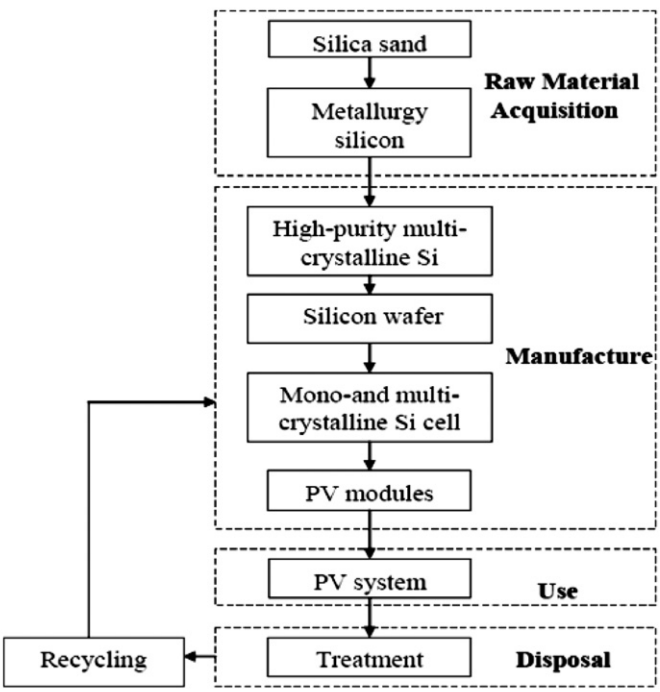

Fig. 30. Life cycle stages of crystalline PV system [125].

cells emits high volume of sulfur oxide, nitrogen oxide and carbon dioxide compared to other PV. Sulfur and nitrogen oxide can combined with water thus producing acidic rain that harms living beings and deteriorate many other materials, while carbon dioxide constitutes the main reason to global warming [126]. The thin film technology is expected to be the future of PV technology with lifetime between 25 and 35 years [127]. However, after they reached their end of lifecycle, they may harm the environment by becoming toxic if not dispose properly [127].

Sherwani et al. [128] did a review on LCA for PV modules based on amorphous, monocrystalline silicon, polycrystalline silicon and other types of PV materials. The results of greenhouse gases emission reviewed in this paper are tabulated in Table 11. Full assessment of the impact of monocrystalline silicon PV module on the environment has been discussed by Phylipsen and Alsema [129]. Comparison studies for three cases of PV i.e., 0.44 m^2, 0.65 m^2 and 1.0 m^2 are considered in this paper. PV with 1 m^2 area shows an obvious low amount of direct process energy requirement for the production of m-Si modules, energy requirements of secondary input materials for m-Si solar cells, gross energy requirement for m-Si modules, energy-related emissions for m-Si modules, acidification and Global warming potential. They also suggested that the use of silver as a contact should be reduced since the source is hard to find and the decommissioning of this material must be done properly to avoid harm to the environment. The use of thin wafers for PV production is also useful to lessen the usage of material. The assessment of environmental impact for polymer solar cell with other solar cell materials was analyzed by Roes et al. [130]. The comparison results between polymer and monocrystalline silicon solar cell for environmental impact such as **NREU**, climate change, abiotic depletion, ozone layer depletion, photochemical oxidant formation, acidification and eutrophication, had shown that polymer showed a good impact with low values for all the factors. They concluded that the polymer technology has less environmental impact as compared to other technologies.

Srivastava et al. [131] conducted the research work on environmental aspects of four major solar cell technologies i.e., multi-crystalline silicon (mc-Si), amorphous silicon (a-Si), cadmium telluride (CdTe) and $CuInSe_2$ (CIS). In this study, the following aspects were considered (i) energy requirements and energy pay-back time, material requirements and resource depletion, environmental emissions, waste handling, possibilities for recycling of modules, occupational health and safety and external safety. For the consideration of emission estimation and risks from cadmium or selenium use in CdTe and CIS modules, respectively, it is acceptable in comparison with some existing products or services like NiCad batteries or coal-fired electricity production. The conclusion of this study is that no single technology score good or excellent on all considered aspects, although future a-Si technology, seems to be the most "environmental friendly" technology, with mc-Si as a good second. The full assessment about CdTe based PV modules and its processing material was also conducted by Fthenakis [132]. They compared the usage of Cd in PV modules and in Ni–Cd battery (Table 12) and concluded that CdTe is a harmful material but during usage in PV module and under normal conditions, it does not generate any emissions. They also discussed on the environmental issues for CdTe in case of fire where glass–glass modules would not be released because Cd dissolves into the molten glass and is retained there. Other comparisons with cadmium emissions from modern coal-powered plants are erroneous because they compare unlikely potential accidental emissions from PV systems to routine (unavoidable) emissions from conventional power plants. In reality, when PV replaces coal burning for electricity generation, it will prevent Cd emissions as well as large quantities of CO_2, NO_x, and particulate emissions.

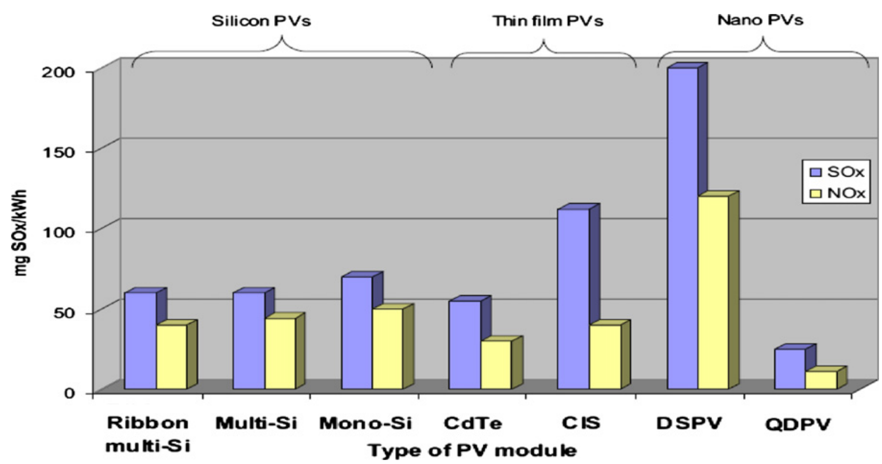

Fig. 31. Sulfur and nitrogen oxide emission from different PV type [126].

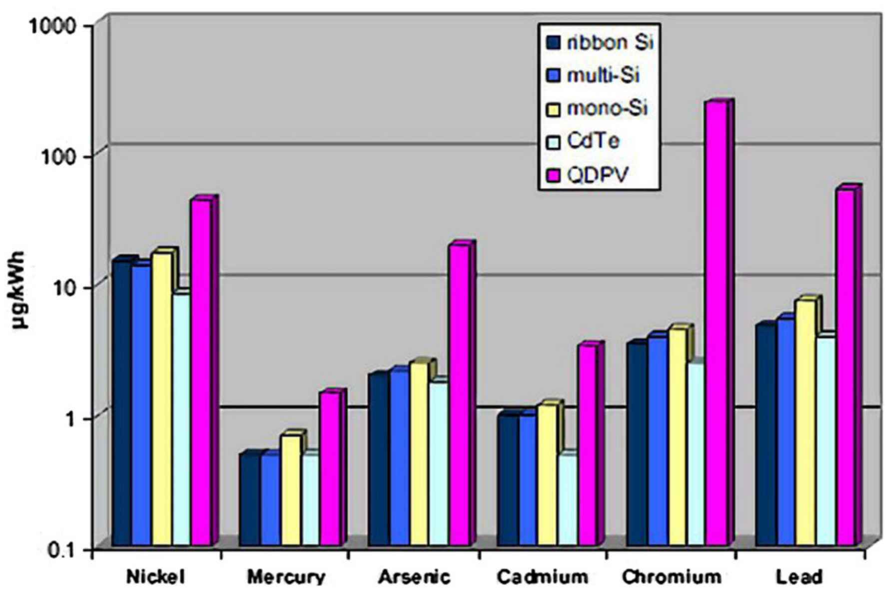

Fig. 32. Heavy metal emission from different PV type [126].

Table 11
Summary of different materials result for greenhouse gases emission **[128]**.

PV type	GHG emission (g-CO_2/kWh$_e$)
Amorphous	47.0
	50.0
	39.0
	34.3
	15.6
Monocrystalline silicon	2820.0
	90.0
	60.0
	64.8
	44.0
	217.0
	165.0
Polycrystalline silicon	12.0
	53.4
	26.4
	104.0
	72.4
	12.1
	9.4
Dye-sensitized	19-47
CIS	16.5
CdTe	15.6

Table 12
Amount of Cd in CdTe PV module and NiCd battery [132].

	g/unit	Mg/kW h (kg/GW h)
PV CdTe	7 g/m^2	1.3
NiCd battery-AA size	3.2	3265
NiCd battery-C size	10.5	3265
NiCd battery-C size	21	3265

The solar cell production has some disadvantages on environment during manufacturing and process time but it is much more advantageous during use. The electricity production through PV system is clean and safe for the environment compared to coal and fossil fuel. The advantages and disadvantages of electrical energy generated from PV technology, coal, fuel and nuclear energy are given in Table 13. The comparisons of PV technology with other renewable energy are compiled in Table 14. From the table, it can be seen that solar PV technology has good potential for environmental protection as a renewable energy source. Furthermore, some of the disadvantages of PV technology related to land can be solved by the help of integrated photovoltaic system (BIPV), which can be installed on

Table 13
Advantages and disadvantages of PV technology compared with nuclear, coal and fuels energy [133].

Advantage/ Disadvantage	PV technology	Nuclear energy	Coal and fuels
Advantage	Low emission of CO_2	Not expensive	High efficiency
	Free source—sun	High efficiency	Conventional electrical energy source
	Infinite source	No air pollution	Power plant can be built anywhere
	Environmental friendly	Reliable	Not expensive
Disadvantage	High start-up cost and investment	Very dangerous	High emission of CO_2 and other hazardous gas
	Low efficiency	Source of uranium are depleting	Source are depleting
	Large area required to install PV system	–	Price increased year by year
	Performance depend on whether and location	–	Source of greenhouse gas

Table 14
PV technology compared with other renewable energy [133].

Advantage/ Disadvantage	Solar power	Tidal power	Wind power	Wave power
Advantage	Low emission of CO_2	No air pollution	Free source	No air pollution
	Free source—sun	Cheap maintenance	No air pollution	Free source of energy
	No moving parts required	Reliable	Economic	Low cost, low maintenance
	Environmental friendly	Use no fuel	May attract tourist	High efficiency
Disadvantage	High start-up cost and investment	Very expensive start-up cost	Whether dependent	Depends on the energy of waves
	Low efficiency	Low efficiency	Noise pollution	Noisy
	Large area required to install PV system. Land use.	Can be install only at certain place	May kill bird that pass by	Need to be built at place where wave can hit strongly
	Performance depend on weather and location	–	–	Need to be able to withstand unpredictable weather

building's wall to save space. Its low efficiency performance due to temperature rising can also be solved since there are many researchers nowadays working on photovoltaic-thermal (PVT) technology, which will enhance the PV efficiency and use it for air and water heating application as well. An overview of the research, development and application aspects for the hybrid photovoltaic/thermal (PV/T) collector systems are discussed by Tyagi et al. [134]. They reviewed about the major research and development works on the photovoltaic/thermal (PVT) hybrid technology. They concluded that solar energy conversion into electricity and heat with a single device (called hybrid photovoltaic–thermal (PVT) collector) has good advancement for future energy demand. Some researches also showed that the PV has good potential in CDM. Purohit and Michaelowa [135] estimated the solar PV (SPV) potential for India and showed that SPV has vast potential of CO_2 mitigation in irrigation water pumping in India. The potential number of SPV pumps is estimated at 70 million. The annual CER potential of SPV pumps in India could theoretically reach 214 million ton if the government would introduce a subsidy system that would allow project developers to close the gap with CER revenues. Under more realistic assumptions about the diffusion of SPV technologies based on past experiences with the government-run programmes, annual CER volumes by 2012 could reach 50,000–100,000 and 0.25–0.75 million by 2020.

Mondal and Sadrul Islam [136] examined the impacts of CO_2 emission reduction target in the Bangladesh power sector during 2005–2035 with the help of solar PV. This analysis was based on a long-term energy system optimization model of Bangladesh using the MARKAL framework. The results of the study showed that on a simple cost base, power generated from solar PV is not yet competitive with that of fossil fuel based power plants. Alternative policies on CO_2 emission constraints reduce the burden of imported fuel, improve energy security and reduce environmental impacts. The cumulative net energy imports during 2005–2035 would be reduced in the range of 33–61% compared to the base scenario and total primary energy requirement would be reduced in the range of 4.5–22.37%. So, solar PV can play an important role in achieving reasonable energy security.

8. Conclusions

The worldwide energy consumption is increasing every year and different technologies are using to produce electricity to compete the energy demand. The environmental pollution is also a serious problem nowadays due to the more use of fossil fuel for energy production. Solar PV technology is growing rapidly in past decades and can play an important role to achieve the high energy demand worldwide. Huge amount of PV systems installed yearly shows the seriousness and the responsibility of every country about the issue to save the earth by using renewable energy. This paper illustrated about the worldwide status of PV technology, research in materials for solar cell, factor affecting for PV efficiency, present cost of solar cell and environmental impact. The conclusion of this review is as:

- Presently, mono- and polycrystalline PV technology have more than 40% market share with 15–17% efficiency. However, thin film, polymer based solar cell and third generation based solar cells are also in development stage and extensive research work is going for efficiency improvement for commercial use.
- The efficiency of solar cell is one of the important parameter in order to establish this technology in the market. The performance of solar cell are also depends on its surrounding such as temperature, irradiation and dust. Temperature can affect PV performance drastically and due to that fact, studies has focus on lowering the temperature by extracting heat and use it for other purpose such as water or air heating. For dust problem, it is advised that PV surface need to be clean often to maintain the performance.
- Every developed technology should have advantages and disadvantages to the environment. The solar cell production has some disadvantages on environment during manufacturing and process time but it gives much more advantages during use. The electricity production through PV system is clean and safe for environment with comparison to coal and fossil fuel. Electricity production through PV module reduces the carbon dioxide emission in environment and safe for global warming problem. The issue related of space for installation of PV is also important but building integrated PV and roof or wall based PV system can solve the

small scale installation. At the end of PV module life, it can be recycled and safely disposal will give minimum effect on environment. So, research for recycled for PV materials are also a key issue for minimizing the environmental effect of PV technology during entire period of life

References

[1] Razykov TM, Ferekides CS, Morel D, Stefanakos E, Ullal HS, Upadhyaya HM. Solar photovoltaic electricity: current status and future prospects. Solar Energy 2011;85:1580–608.
[2] Technology roadmap-solar photovoltaic energy. International energy agency, 〈http://www.iea-pvps.org〉; 2010.
[3] The solar photovoltaic electricity empowering the world 2011. EPIA report, 〈http://www.greenpeace.org/international/en/publications/reports/Solar-Generation-6/〉.
[4] Jäger-Waldau A, Szabó M, Monforti-Ferrario F, Bloem H, Huld T, Lacal Arantegui R Renewable energy snapshots 2011, 〈http://www.jrc.ec.europa.eu/〉.
[5] PV status report, (2011), 〈www.ncpre.iitb.ac.in/userfiles/files/PV_Status_Report_2011.pdf〉.
[6] Lloyd B, Forest AS. The transition to renewables: can PV provide an answer to the peak oil and climate change challenges? Energy Policy 2010;38:7378–94.
[7] 〈http://solarcellcentral.com〉.
[8] 〈http://india.gov.in/allimpfrms/alldocs/15657.pdf〉.
[9] Wu H, Hou Y. Recent development of grid-connected PV systems in China. Energy Procedia 2011;12:462–70.
[10] Global market outlook until 2014, European Photovoltaic Industry Association report, (2010), 〈http://www.epia.org/fileadmin/EPIA_docs/public/Global_Market_Outlook_for_Photovoltaics_until_2014.pdf〉.
[11] 〈http://www.enf.cn/database/panels-csg-p.html〉.
[12] 〈http://optics.org/indepth/3/3/1/PVrankingsb〉.
[13] McCann MJ, Catchpole KR, Weber KJ, Blakers AW. A review of thin film crystalline silicon for solar cell applications. Part 1: Native substrates. Solar Energy Materials and Solar Cells 2001;68:135–71.
[14] El Chaar L, Lamont LA, El Zein N. Review of photovoltaic technologies. Renewable and Sustainable Energy Reviews 2011;15:2165–75.
[15] Gorter T, Reinders AHME. A comparison of 15 polymers for application in photovoltaic modules in PV-powered boats. Applied Energy 2012;92:286–97.
[16] Global market outlook for photovoltaics until 2012. 〈http://www.epia.org/index.php?id=18〉.
[17] 〈http://en.wikipedia.org/wiki/File:Silicon-unit-cell-labelled-3D-balls.png〉.
[18] 〈http://en.wikipedia.org/wiki/Czochralski_process〉.
[19] Becker C, Sontheimer T, Steffens S, Scherf S, Rech B. Polycrystalline silicon thin films by high-rate electronbeam evaporation for photovoltaic applications—influence of substrate texture and temperature. Energy Procedia 2011;10:61–5.
[20] Manna TK, Mahajan SM. Nanotechnology in the development of photovoltaic cells. IEEE 2007:379–86.
[21] 〈http://www.evergreensolar.com〉.
[22] Satyen KD. Recent developments in high efficiency photovoltaic cells. Renewable Energy 1998;15:467–72.
[23] Fundamentals of PV material, (1998), 〈userwww.sfsu.edu/∼ciotola/solar/pv.pdf〉.
[24] Iles PA. Evolution of space solar cells. Solar Energy Materials and Solar Cells 2001;68:1–13.
[25] Vrielink JAM, Tiggelaar RM, Gardeniers JGE, Lefferts L. Applicability of X-ray fluorescence spectroscopy as method to determine thickness and composition of stacks of metal thin films: a comparison with imaging and profilometry. Thin Solid Films 2012;520:1740–4.
[26] Parida B, Iniyan S, Goic R. A review of solar photovoltaic technologies. Renewable and Sustainable Energy Reviews 2011;15:1625–36.
[27] Boutchich M, Alvarez J, Diouf D, Cabarrocas PRi, Liao M, Masataka I, et al. Amorphous silicon diamond based heterojunctions with high rectification ratio. Journal of Non-Crystalline Solids 2012 Article in Press.
[28] Radue C, van Dyk EE, Macabebe EQ. Analysis of performance and device parameters of CIGS PV modules deployed outdoors. Thin Solid Film 2009;517:2383–5.
[29] Britt J, Ferekides C. Applied Physics Letters 1993;62:2851.
[30] Hegedus SS, McCandless BE. CdTe contacts for CdTe/CdS solar cells: effect of Cu thickness surface preparation and recontacting on device performance and stability. Solar Energy Materials and Solar Cells 2005;88:75–95.
[31] Boer KW. Cadmium sulfide enhances solar cell efficiency. Energy Conversion and Management 2011;52:426–30.
[32] Critical materials for sustainable energy applications. Resnick Institute Report California. September 2011. 〈www.resnick.caltech.edu/learn/docs/ri_criticalmaterials_report.pdf〉.
[33] Soliman MM, Shabana MM, Abulfotuh F. CdS/CdTe solar cell using sputtering technique. WREC 1996:386–9.
[34] Repins I, Conteras M, Egaas B, DeHart C, Scharf J, Perkins CL. 19.9% efficient $ZnO/CdS/CuInGeSe_2$ solar cell with 81.2% fill factor. Progress in Photovoltaics: Research and Applications 2008;16:235–9.
[35] Meyer EL, van Dyk EE. Characterization of degradation in thin film photovoltaic module performance parameters. Renewable Energy 2003;28:1455–69.
[36] Goetzberger A, Hebling C, Schock HW. Photovoltaic materials, history, status and outlook. Materials Science and Engineering R 2003;40:1–46.
[37] Riken Jeiki Co., Ltd., 〈http://www.ac-2.com/AC_En/app_SC.html〉.
[38] 〈http://www2.warwick.ac.uk〉.
[39] Peumans P, Yakimov A, Forrest SR. Small molecular weight organic thin-film photodetectors and solar cells. Journal of Applied Physics 2003;93:3693–723.
[40] Itoh M, Takahashi H, Fujii T, Takakura H, Hamakawa Y, Matsumoto Y. Evaluation of electric energy performance by democratic module PV system field test. Solar Energy Materials and Solar Cells 2001;67:435–40.
[41] Wu L, Tian W, Jiang X. Silicon based solar cell system with a hybrid PV module. Solar Energy Materials and Solar Cells 2005;87:637–45.
[42] Nazeeruddin MdK, Baranoff E, Gratzel M. Dye-sensitized solar cells: a brief overview. Solar Energy 2011;85:1172–8.
[43] Grätzel M. Dye-sensitized solar cells. Journal of Photochemistry and Photobiology C: Photochemistry Reviews 2003;4:145–53.
[44] Wu CY, Mathews JA. Knowledge flows in the solar photovoltaic industry: Insights from patenting by Taiwan, Korea, and China. Research Policy 2012;41:524–40.
[45] Serrano E, Rus G, Garcia-Martinez J. Nanotechnology for sustainable energy. Renewable and Sustainable Energy Reviews 2009;13:2372–84.
[46] Sethi VK, Pandey M, Shukla P. Use of nanotechnology in solar PV cell. International Journal of Chemical Engineering and Applications 2011;2.
[47] 〈http://www.nano.gov〉.
[48] 〈http://www.news.cornell.edu/stories/Sept09/NanotubeSolarCells.html〉.
[49] Kumar P, Deep A, Sharma SC, Bharadwaj LM. Bioconjugation of InGaP quantum dots for molecular sensing. Analytical Biochemistry 2012;421:285–90.
[50] Aroutiounian V, Petrosyan S, Khachatryan A. Studies of the photocurrent in quantum dot solar cells by the application of a new theoretical model. Solar Energy Materials and Solar Cells 2005;89:165–73.
[51] Gorji NE. A theoretical approach on the strain-induced dislocation effects in the quantum dot solar cells. Solar Energy 2012;86:935–40.
[52] Chen J, Zhao DW, Song JL, Sun XW, Deng WQ, Liu XW, et al. Directly assembled CdSe quantum dots on TiO_2 in aqueous solution by adjusting pH value for quantum dot sensitized solar cells. Electrochemistry Communications 2009;11:2265–7.
[53] Ross RT, Nozik AJ. Efficiency of hot carrier solar energy converters. Journal of Applied Physics 1982;53:3813–8.
[54] Hosenberg CB, Barnett AM, Kirkpatrick D Nanostructured solar cells for high efficiency photovoltaics. IEEE fourth world conference on photovoltaic energy conversion, WCPEC-4 2007; 2:2565–8.
[55] Konig D, Casalenuovo K, Takeda Y, Conibeer G, Guillemoles JF, Patterson R, et al. Hot carrier solar cells: principles, materials and design. Physica E 2010;42:2862–6.
[56] Zhao J, Wang A, Campbell P, Green. MA. A 19.8% efficient honeycomb multicrystalline silicon solar cell with improved light trapping. IEEE Transactions on Electron Devices 1999;46:1978–83.
[57] 〈http://am.suntech-power.com/〉.
[58] 〈http://www.yinglisolar.com〉.
[59] 〈http://www.trinasolar.com/〉.
[60] 〈http://www.canadiansolar.com/〉.
[61] 〈http://www.sharp-solar.com〉.
[62] 〈http://www.hanwha-solarone.com/〉.
[63] 〈http://www.jinkosolar.com/〉.
[64] 〈http://www.ldksolar.com〉.
[65] 〈http://www.solarworld-usa.com〉.
[66] Glunz SW. New concepts for high-efficiency silicon solar cells. Solar Energy Materials and Solar Cells 2006;90:3276–84.
[67] Tsunomura Y, Yoshimine Y, Taguchi M, Baba T, Kinoshita T, Kanno H, et al. Twenty-two percent efficiency HIT solar cell. Solar Energy Materials and Solar Cells 2009;93:670–3.
[68] Mishima T, Taguchi M, Sakata H, Maruyama E. Development status of high-efficiency HIT solar cells. Solar Energy Materials and Solar Cells 2011;95:18–21.
[69] Chen A, Zhu K. Computer simulation of a-Si/c-Si heterojunction solar cell with high conversion efficiency. Solar Energy 2012;86:393–7.
[70] Friedman DJ. Progress and challenges for next-generation high-efficiency multijunction solar cells. Current Opinion in Solid State and Materials Science 2010;14:131–8.
[71] Yamaguchi M, Takamoto T, Araki K. Super high-efficiency multi-junction and concentrator solar cells. Solar Energy Materials and Solar Cells 2006;90:3068–77.
[72] Rannels JE. The case for a 40% efficiency goal for photovoltaic cells in 2005. Solar Energy Materials and Solar Cells 2001;65:3–8.
[73] Engelhart P, Wendt J, Schulze A, Klenke C, Mohr A, Petter K, et al. R&D pilot line production of multi-crystalline Si solar cells exceeding cell efficiencies of 18%. Energy Procedia 2011;8:313–7.
[74] Zhao J. Recent advances of high-efficiency single crystalline silicon solar cells in processing technologies and substrate materials. Solar Energy Materials and Solar Cells 2004;82:53–64.
[75] Gu X, Yu X, Guo K, Chen L, Wang D, Yang D. Seed-assisted cast quasi-single crystalline silicon for photovoltaic application: towards high efficiency and low cost silicon solar cells. Solar Energy Materials and Solar Cells 2012;101:95–101.

[76] Fleischer K, Arca E, Shvets IV. Improving solar cell efficiency with optically optimized TCO layers. Solar Energy Materials and Solar Cells 2012;101: 262–9.
[77] Clement F, Menkoe M, Kubera T, Harmel C, Hoenig R, Wolke W, et al. Industrially feasible multi-crystalline metal wrap through (MWT) silicon solar cells exceeding 16% efficiency. Solar Energy Materials and Solar Cells 2009;93:1051–5.
[78] Morikawa H, Nishimoto Y, Naomoto H, Kawama Y, Takami A, Arimoto S, et al. 16.0% efficiency large area (10 cm × 10 cm) thin film polycrystalline silicon solar cell. Solar Energy Materials and Solar Cells 1998;53:23–8.
[79] Ito S, Murakami TN, Comte P, Liska P, Grätzel C, Nazeeruddin MK, et al. Fabrication of thin film dye-sensitized solar cells with solar to electric power conversion efficiency over 10%. Thin Solid Films 2008;516:4613–9.
[80] Yamaguchi T, Tobe N, Matsumoto D, Nagai T, Arakawa H. Highly efficient plastic-substrate dye-sensitized solar cells with validated conversion efficiency of 7.6%. Solar Energy Materials and Solar Cells 2010;94:812–6.
[81] Yamaguchi T, Uchida Y, Agatsuma S, Arakawa. H. Series-connected tandem dye-sensitized solar cell for improving efficiency to more than 10%. Solar Energy Materials and Solar Cells 2009;93:733–6.
[82] Shenck NS. Alternative energy systems. U.S. Naval Academy Lecture Readings; 2010.
[83] Dincer F, Meral ME. Critical factors that affecting efficiency of solar cells. Smart Grid and Renewable Energy 2010;1:47–50.
[84] Kalogirou S. Solar energy engineering: processes and systems: chapter 9. Academic Press; 2009 pp. 469–517.
[85] Kumar R, Rosen MA. A critical review of photovoltaic-thermal solar collectors for air heating. Applied Energy 2011;88:3603–14.
[86] P Singh,NM.Ravindra. Temperature dependence of solar cell performance-an analysis, Solar Energy Materials and Solar Cells, 101, (2012), 36–45.
[87] Ting CC, Chao WS. Measuring temperature dependence of photoelectric conversion efficiency with dye-sensitized solar cells. Measurement 2010;43: 1623–7.
[88] Berginc M, Krasovec UO, Hocevar M, Topic M. Performance of dye-sensitized solar cells based on ionic liquids: effect of temperature and iodine concentration. Thin Solid Films 2008;516:7155–9.
[89] Rodriguez DM, Horley PP, Hernandez JG, Vorobiev YV, Gorley PN. Photovoltaic solar cells performance at elevated temperatures. Solar Energy 2005;78:243–50.
[90] Evans DL. Simplified method for predicting photovoltaic array output. Solar Energy 1981;27:555–60.
[91] Goossens D, Kerschaever EV. Aeolian dust deposition on photovoltaic solar cells: the effects of wind velocity and airborne dust concentration on cell performance. Solar Energy 1999;66:277–89.
[92] Jiang H, Lu L, Sun K. Experimental investigation of the impact of airborne dust deposition on the performance of solar photovoltaic (PV) modules. Atmospheric Environment 2011;45:4299–304.
[93] Elminir HK, Ghitas AE, Hamid RH, El-Hussainy F, Beheary MM, Abdel-Moneim KM. Effect of dust on the transparent cover of solar collectors. Energy Conversion and Management 2006;47:3192–203.
[94] Sulaiman SA, Hussain HH, Razali NSHNLMSI. Effects of dust on the performance of PV panels. World Academy of Science Engineering and Technology 2011;58:588–93.
[95] Kaldellis JK, Kapsali M. Simulating the dust effect on the energy performance of photovoltaic generators based on experimental measurements. Energy 2011;36:5154–61.
[96] El-Shobokshy MS, Hussein FM. Effect of dust with different physical properties on the performance of photovoltaic cells. Solar Energy 1993;51: 505–11.
[97] Hee JY, Kumar LV, Danner AJ, Yang. H, Bhatia CS. The effect of dust on transmission and self-cleaning property of solar panels. Energy Procedia 2012;15:421–7.
[98] Koutroulis E, Kalaitzakis K, Tzitzilonis V. Development of an FPGA-based system for real-time simulation of photovoltaic modules. Microelectronics Journal 2009;40:1094–102.
[99] Eikelboom JA, Jansen MJ. Characterisation of PV modules of new generations. Results of tests and simulations 2000.
[100] Huld T, Muller R, Gambardella A. A new solar radiation database for estimating PV performance in Europe and Africa. Solar Energy 2012; 86(6):1803–1815..
[101] Thongpron J, Kirtikara K. Effects of low radiation on the power quality of a distributed PV-grid connected system. Solar Energy Materials and Solar Cells 2006;90:2501–8.
[102] Gottschalg R, Infield DG, Kearney MJ. Experimental study of variations of the solar spectrum of relevance to thin film solar cells. Solar Energy Materials and Solar Cells 2003;79:527–37.
[103] Yoo SH. Simulation for an optimal application of BIPV through parameter variation. Solar Energy 2011;85:1291–301.
[104] Meral ME, Dinçer F. A review of the factors affecting operation and efficiency of photovoltaic based electricity generation systems. Renewable and Sustainable Energy Reviews 2011;15:2176–84.
[105] Maycock PD. Cost reduction in PV manufacturing impact on grid connected and building integrated markets. Solar Energy Materials and Solar Cells 1997;47:37–45.
[106] Solar generation 6 solar photovoltaic electricity empowering the world 2011, EPIA, 〈www.epia.org/publications/epiapublications/solar-generation-6.html〉.
[107] Ranjan S, Balaji S, Panella RA, Ydstie BE. Silicon solar cell production. Computers and Chemical Engineering 2011;35:1439–53.
[108] 〈http://www.solar-facts-and-advice.com/cadmium-telluride.html〉.
[109] 〈http://www.easyecoblog.com/140/new-2009-solar-federal-tax-credit/〉.
[110] Adams A, Subbaiah V, Chowdhary A Cost analysis comparison of bloom energy fuel cells with solar energy technology and traditional electric companies. A project report presented to the Faculty of the Department of General Engineering, San Jose State University, April 2011.
[111] Powell DM, Winkler MT, Choi HJ, Simmons CB, Needleman DB, Buonassisi T. Crystalline silicon photovoltaics: a cost analysis framework for determining technology pathways to reach base load electricity costs. Energy & Environmental Science 2012;5:5874.
[112] 〈http://www.solarshop-europe.net〉.
[113] 〈http://www.amazon.com〉.
[114] Kong K. The solar power (photovoltaic) industry in victoria: market forces, emerging industry structure and potential areas of value creation and competitive advantage for business enterprises. PEC 2010;624.
[115] Krebs FC. Fabrication and processing of polymer solar cells: a review of printing and coating techniques. Solar Energy Materials and Solar Cells 2009;93:394–412.
[116] Kalowekamo J, Baker E. Estimating the manufacturing cost of purely organic solar cells. Solar Energy 2009;83:1–8.
[117] Nielsen TD, Cruickshank C, Foged S, Thorsen J, Krebs FC. Business, market and intellectual property analysis of polymer solar cells. Solar Energy Materials and Solar Cells 2010;94:1553–71.
[118] Emmott CJM, Urbina A, Nelson J. Environmental and economic analysis assessment of ITO-free electrodes for organic solar cells. Solar Energy Materials and Solar Cells 2012;97:14–21.
[119] Branker K, Pathak MJM, Pearce JM. A review of solar photovoltaic levelized cost of electricity. Renewable and Sustainable Energy Reviews 2011;15: 4470–82.
[120] Laird J. Supplying solar PV: the solar photovoltaic (PV) industry is entering a new phase, and needs to innovate and reduce costs. Renewable Energy Focus 2011;12:72–7.
[121] Ramanathan K, Contreras MA, Perkins CL, Asher S, Hasoon FS, Keane J, et al. Properties of 19.2% efficiency $ZnO/CdS/CuInGaSe_2$ thin-film solar cells. Progress in Photovoltaics 2003;11:225–30.
[122] Palm J, Probst V, Brummer A, Stetter W, Tölle R, Niesen TP, et al. CIS module pilot processing applying concurrent rapid selenization and sulfurization of large area thin film precursors. Thin Solid Films 2003;431:514–22.
[123] Sharma MC, Tripathi B, Kumar S, Srivastava S, Vijay YK. Low cost $CuInSe_2$ thin films production by stacked elemental layers process for large area fabrication of solar cell application. Materials Chemistry and Physics 2012;131:600–4.
[124] Aguado-Monsonet MA The environmental impact of photovoltaic technology. January 1998.
[125] Zhang J, Lv F, Zhang L. Discussion on environment impact assessment in the lifecycle of PV systems. Energy Procedia 2012;16:234–9.
[126] Sengül H, Theis TL. An environmental impact assessment of quantum dot photovoltaics (QDPV) from raw material acquisition through use. Journal of Cleaner Production 2011;19:21–31.
[127] Berger W, Simon FG, Weimann K, Alsema EA. A novel approach for the recycling of thin film photovoltaic modules. Resources, Conservation and Recycling 2010;54:711–8.
[128] Sherwani AF, Usmani JA, Varun. Life cycle assessment of solar PV based electricity generation systems: a review. Renewable and Sustainable Energy Reviews 2010;14:540–4.
[129] Phylipsen GJM,Alsema EA Environmental life-cycle assessment of multi-crystalline silicon solar cell modules. September 1995. Report no. 95057.
[130] Roes AL, Alsema EA, Blok K, Patel MK. Ex-ante environmental and economic evaluation of polymer photovoltaics. Progress in Photovoltaics: Research and Applications 2009;17:372–93.
[131] Srivastava MK, Gupta SKr, Gupta A Environmental aspects of solar cell modules. Department of electronics engineering, MPEC, Kothi Mandhana, Kanpur.
[132] Fthenakis VM. Life cycle impact analysis of cadmium in CdTe PV production. Renewable and Sustainable Energy Reviews 2004;8:303–34.
[133] 〈http://www.darvill.clara.net〉.
[134] Tyagi VV, Kaushik SC, Tyagi SK. Advancement in solar photovoltaic/thermal (PV/T) hybrid collector technology. Renewable and Sustainable Energy Reviews 2012;16:1383–98.
[135] Purohit P, Michaelowa A. CDM potential of SPV pumps in India. Renewable and Sustainable Energy Reviews 2008;12:181–99.
[136] Mondal MdAH, Sadrul Islam AKM. Impacts of CO_2 emission constraints on penetration of solar PV in the Bangladesh power sector. Renewable Energy 2012;43:418–22.